OPTIMAL SEQUENCING OF MULTIPLE CROPPING SYSTEMS

By

YOU JEN TSAI

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Chairman: Dr. J. W. Jones
Cochairman: Dr. J. W. Mishoe
Major Department: Agricultural Engineering

Multiple cropping is one of the means to increase or at least stabilize net farm income where climatic and agronomic conditions allow its use, such as in Florida. With several crops to be examined simultaneously, the design of multiple cropping systems becomes complex. Therefore, a systems approach is needed. The goal of this study is to develop a mathematical method as a framework for optimizing multiple cropping systems by selecting cropping sequences and their management practices as affected by weather and cropping history.

Several alternative formulations of multiple cropping problems were studied with regard to their practicality for solutions. A deterministic activity network model that combined simulation and optimization techniques has been developed to study this problem. In

particular, to study irrigation management in multiple cropping systems, models of crop yield response, crop phenology, and soil water were used to simulate the network. Then, the K longest paths algorithm was applied to optimize cropping sequences.

Under a non-irrigated field in north Florida, winter wheat followed by either soybean, corn, or peanut was found to be the most profitable cropping system. Especially favorable was the cropping of wheat-peanut. Another significant conclusion to be drawn concerned the effect of irrigation management on multiple cropping sequences. Under irrigated fields, peanuts were selected for production each year because of their high net returns in comparison to the other crops. In a system in which peanut was not considered as an option, inclusion of irrigated wheat-corn cropping would not be a profitable multiple cropping system. Instead, double cropping of corn-soybean was the dominant optimal sequence under irrigation.

The importance of irrigation management in multiple cropping systems was studied using the methodology developed. The methodology is also capable of incorporating other aspects of farming (i.e. pest management) into an integrated framework for determining optimal cropping sequences.

CHAPTER I
INTRODUCTION

Net farm income has been a major concern for farmers in commercial agriculture for a long time. Income has expanded through various ways including an increase in land area for production, fertilizer and pesticide applications, machinery and other capital expansions. However, these different methods of increasing net farm income usually increase the cost of production. A study (Ruhimbasa, 1983) showed that multiple cropping had the potential to reduce costs per unit of output and reduce production risks, and therefore could increase or at least stabilize net farm income where climatic and agronomic conditions allow its use.

Multiple cropping may also be called sequential or succession cropping. Succession cropping is the growing of two or more crops in sequence on the same field during a year. The succeeding crop is planted after the preceding crop has been harvested. There is no intercrop competition. Only one crop occupies the field at one time; thus mechanization is possible.

In summary, multiple cropping increases annual land use and productivity resulting in increased total food production per unit of land. It also allows more efficient use of solar radiation and nutrients by diversifying crop production. Thus, it reduces risk of total crop loss and helps stabilize net farm income.

The Problem

Multiple cropping is not without risk. The use of multiple cropping creates new management problems. It may create time conflicts for land and labor, may require new varieties or new crops for an area, may deplete soil resources, i.e. water and nutrient reserves, more rapidly, and may cause residuals from one crop that directly affect the next crop. For example, increasing the crop species grown on the same land makes herbicide selection more complex. Disease incidence may increase with an annual production of the same species on the same field each year. As a result, higher levels of management become more important in terms of operations needed. In designing optimal multiple cropping systems, managers need to take into consideration these effects.

Of the above management areas, timing becomes dominant for successful multiple cropping, given substantial yield losses for each day of delay. As estimated by Phillips and Thomas (1984), if the losses of soybean yields after a given date are 62 - 75 kg/ha-day, the cash losses on a 200-ha planting of soybeans would be as much as $4000 - $5000/day. A delay of one week probably could make the difference between profit and loss. Therefore, a timely planting and optimal within-season management practices are the key to profitable multiple cropping.

Soil water determines whether seeds will germinate and seedlings become established. With multiple cropping, seed zone water is even more critical because the second crop must be established rapidly to avoid possible yield reduction due to frost. Also, because of depletion

by the preceding crop, soil water content at planting of subsequent crops in multiple cropping systems may be low as compared to planting following a fallow period. This is particularly true in areas of low rainfall or where periodic droughts could result in a depleted soil reservoir that would prevent successful planting and production of the second crop. Hence, management practices that take advantage of soil water storage should be beneficial in multiple cropping systems.

Plant growth is influenced by the process of evapotranspiration (ET). During the time course of a seasonal crop, the crop system changes from one in which ET is entirely soil evaporation to one in which ET is mostly plant transpiration, and finally to one in which both plant transpiration and soil evaporation are affected by crop senescence. Plants store only a minor amount of the water they need for transpiration; thus, the storage reservoir furnished by the soil and its periodic recharge are essential in maintaining continuous growth. In the event of relatively high ET demand coupled with depleted soil water conditions, water deficits in plants occur as potential gradients develop to move water against flow resistances in the transpiration pathway. As plants become water stressed, their stomata close. The resulting effects on transpiration and photosynthesis are essentially in phase. This would represent the reduction of plant growth because of less carbon dioxide uptake and reduced leaf and stem growth. Therefore, soil water, undoubtedly more often than any other factors, determines crop yield.

The soil water reservoir is supplied by rainfall. As evapotranspiration demand and supply of soil water are synchronized, potential maximum yield is expected. Otherwise, irrigation may be

practiced to supplement rainfall supply of water to the soil and thus avoid possible yield reductions. Hence, crop sequencing that shifts crop demands for soil water according to weather patterns could be beneficial in multiple cropping systems.

In Florida, where the cold season is short and the water supply (precipitation or irrigation) is sufficient to grow two or more crops per year on the same field, the potential of practicing multiple cropping is high. However, water management is critical here. For instance, although long-term average rainfall amount (148 cm per year) may be sufficient on the average for replenishing the soil water supply, year-to-year variability in rainfall amounts and the variability in successive days without rain may result in one or more drought periods during a growth season. On the other hand, irrigation development is expensive. Inasmuch as benefits from irrigation may vary appreciably from year to year, developing optimal multiple cropping systems is intended to make maximum use of the expensive irrigated land.

As the number of crops, number of varieties, variability in soil, and development of new integrated management systems (i.e., tillage, irrigation, pest control, fertilization, weed control, etc.) increase, planning of a multiple cropping production system becomes very complex in terms of maximizing net farm income. However, actual experimentation with the system may be infeasible, cost-ineffective, and time-consuming due to the vast array of multiple cropping systems that possibly can be grown. As a result, an alternate method for evaluating optimal multiple cropping practices is needed.

At a field level, it is desirable to be able to select crops, varieties, planting date, and to evaluate various management strategies

in a multiple cropping scheme. The overall goal of this study is to develop a mathematical method as a framework for optimizing multiple cropping systems by selecting cropping sequences and their management practices as affected by weather pattern and cropping history. This framework will be applied in particular to the study of irrigation management in multiple cropping production.

Scope of the Study

Many efforts have contributed to developing irrigation programs which would provide optimal return to growing a single crop during a single season. Fewer studies have concentrated on investigating the effect of irrigation management under multiple cropping systems. The problem to be explored is as follows. A 'field' is considered for growing crops over an N-year production horizon. There are I number of potential crops and each crop has J varieties to be considered. Only one crop grows at one time and various idle periods are also considered legitimate choices in a cropping sequence. Under the assumption that other production practices are optimally followed, what are optimal cropping sequences and associated within-season irrigation strategies that maximize net discounted return?

This study at a field-level needs to be differentiated from that of a farm-level system. A field can be defined as an unit area of uniform-soil land or as an area constrained by the inherent operational practicalities of the irrigation system used. For example, it may be the area under a center pivot irrigation system. Applying systems analysis methods, this study develops a mathematical model to optimize multiple cropping systems.

Objectives

The specific objectives of the study are

1. To develop a framework for optimal sequencing of crops in a multiple cropping production system and for determining optimal management of the crop land.
2. To apply the framework to study irrigation management in multiple cropping production.
3. To implement a computer model for North Florida soil and climate conditions, taking soybean, corn, peanut, and wheat as crops to be produced.
4. To perform field experiments designed to quantify the effect of water stress on wheat yield for Florida conditions, and to form a simplified wheat yield response model for use in the analysis.
5. To use the model as a decision-making tool to analyze multiple cropping practices in this region in order to increase net farm income.

CHAPTER II
LITERATURE REVIEW

Multiple Cropping

In the United States, sequential cropping systems are mostly found in southern states where a short cold season allows the planting of a second or a third crop on the same land. The use of no-tillage methods further enhances the success of sequential cropping systems in this region. A selected number of articles concerning the topics are reviewed.

Multiple cropping in sequence has been criticized for being yield reducing. Crabtree and Rupp (1980) found that in Oklahoma wheat yield decreased from 2519 kg/ha in a monocropping system to 2200 kg/ha in a double cropping system. The following soybean yield decreased from 2000 kg/ha in 51-cm rows and 1792 kg/ha in 76-cm rows to 1603 and 1453 kg/ha, respectively. The use of no-tillage practices increased soybean yield to 1722 and 1543 kilogram per hectare in the double cropping system. In fact, the long land preparation process in the conventional tillage method led to a late planting for the second crop which resulted in lower yields. The no-tillage method, allowing a direct planting of crops into unprepared soil with standing crops or residues, had significant impacts on reducing the risk of obtaining low yield due to late planting in a multiple cropping system. Westberry and Gallaher (1980) conducted two different studies on the influence of tillage

practices on yield which also led to a conclusion favoring a no-tillage method.

The potential of no-tillage methods to reduce production costs when associated with multiple cropping systems to increase land productivity suggests that these two practices should be used together to increase net farm income (Robertson et al., 1980). Other advantages of no-tillage systems become more apparent with multiple cropping, and these include (1) elimination of moisture loss associated with conventional tillage at planting time, ensuring stands of second and third crops under restricted rainfall patterns; (2) further reduction of soil erosion; and (3) maintenance of soil structure by elimination of plowing and land preparation (Phillips and Thomas, 1984.)

It is obvious that multiple cropping for grain crops depends on a reasonably long frost-free season. Guilarte (1974) and Smith (1981) indicated that a double cropping system can be feasible during the 240 or more days of the warm growing season in north and west Florida. Unfortunately, these long growing seasons are associated with elevated temperatures, which may adversely depress the second crop yield as witnessed by Widstrom and Young (1980). Their results showed that double cropping of corn could be a viable option on the coastal plain of the southeastern United States, when the second crop was taken as forage rather than as grain.

To generalize types of multiple cropping on a cropping-year basis, we divide it into winter-summer double cropping, summer-summer double cropping and winter-summer-summer triple cropping. The major system of winter-summer double cropping is wheat-soybeans (Gallaher and Westberry, 1980). The use of valuable irrigation water for a second crop of

sorghum or sunflower is not very practical except to produce favorable emergence condition. Thus, soybean is favored as a second crop. Of summer-summer systems, corn-soybeans appears to be most commercially viable (Gallaher et al., 1980). Because soybeans bloom over a longer period of time, their yields tend to be hurt less by short periods of drought during flowering. Corn, on the other hand, requires excellent soil water conditions during silking and tasseling, or else yields will be low. The third multiple cropping system is adding a winter vegetable crop to summer crops or following a winter-summer sequence with a late fall planting of a cool-season vegetable. This type of system has the advantage of producing the vegetable crop when prices are relatively high, and still producing field crops competitively with the rest of the nation.

Despite other attributes of multiple cropping, if it does not, over a period of time, provide more net income to the farmer, it will not be practiced. Economic analyses studied by a group of research scientists in the University of Georgia indicated that irrigated agronomic crops were generally profitable on a first-crop basis, but the profitable agronomic second-crop was limited to sorghum and soybeans (Anonymous, 1981). In 1980, the study also showed that most irrigated multiple cropping production was profitable on the well-drained, sandy soil. Both irrigated and dryland peanut production were profitable; however, irrigated peanuts were more profitable. Irrigated corn was also more profitable than nonirrigated corn. Tew et al. (1980) further analyzed costs and returns of irrigated, double-crop sweet corn and soybean production. They concluded that irrigated soybean as the second crop in a double-crop system was a questionable alternative since net returns

did not compare favorably with dryland production. However, irrigation of soybean as the second crop was still justified because it reduced income variance.

These results suggest that the economics of multiple cropping systems differs significantly from that of a single, full season monocrop. Knowledgeable management practices such as precise planting dates, cultivars, and water management are essential. Gallaher et al. (1980) strongly asserted that "if growers use management practices in these studies, corn-soybean succession cropping can be successful in Florida" (page 4).

Optimization Models of Irrigation

In order to study irrigation policies to maintain favorable soil moisture conditions and thus avoid economic yield reduction, optimization techniques have been increasingly used for the last 15 years. Mathematical models are inherent in this methodology. Implicitly or explicitly a crop response model within the mathematical statement of the objective function is required. Furthermore, the soil water status, needed as a set of constraints in the optimization problem, is traditionally calculated in a soil water balance model. Then, various optimization techniques are applied for finding the best or optimal decisions in an organized and efficient manner. The role of models and simulation in irrigation optimization problems is reviewed herein.

Soil Water Balance

Water balance models for irrigation scheduling were developed as 'bookkeeping' approaches to estimate soil water availability in the root zone.

$$S_n = S_{n-1} + P_n + I_n + DR_n - ET_n - RO_n - PC_n \qquad (2.1)$$

where S_n = soil water content on the end of day n,

P_n = total precipitation on day n,

I_n = total irrigation amount on day n,

DR_n = water added to root zone by root zone extension,

ET_n = actual evapotranspiration on day n,

RO_n = total runoff on day n, and

PC_n = deep percolation on day n.

In general, a volume of soil water, defined in terms of the soil water characteristics and the root zone of the crop being irrigated, is assumed to be available for crop use. Depletions from this reservoir by evapotranspiration (ET) are made on a daily basis. Soil water balance models generally are classified into two categories: (a) those based on the assumption that water is uniformly available for plant use between the limits of field capacity and permanent wilting point, and (b) those based on the assumption that transpiration rates were known functions of soil water potential or water content (Jones and Smajstrla, 1979).

Uniformly available soil water. Models based on the assumption of uniformly available soil moisture between field capacity and permanent wilting point simulated water use based on climatic variables only.

Those simulation models for ET by various crops have been summarized by Jensen (1973). For ET prediction, a technique used widely to calculate potential ET is the modified Penman equation (Van Bavel, 1966). The Penman equation predicted reference ET (ET_p), which is that of a well-watered, vegetated surface. To predict actual rather than reference ET for a well-watered crop, a crop coefficient, K_c, was introduced (Jensen, 1973) as

$$ET = K_c * ET_p \qquad (2.2)$$

Crop coefficients for specific crops must be determined experimently. They represent the expected relative rate of ET if water availability does not limit crop growth. The magnitude of the crop coefficient is a function of the crop growth stage. One of the major shortcomings of this method is that they do not account for changes in ET rates due to changing soil water levels.

Limiting soil water. To correct this shortcoming, a number of researchers (Ritchie, 1972; Kanemasu et al., 1976) have developed models to predict ET as functions of both climatic demands and soil water availability. This resulted in a more complex model than the Penman equation, which uses climatic indicators only. Ritchie's model separated evaporation and transpiration components of water use. Potential evaporation E_p from a wet soil surface under a row crop (energy limiting) was defined as

$$E_p = \frac{\tau}{\alpha} * ET_p \qquad (2.3)$$

where τ = reduction factor due to crop cover, and α = proportionality constant due to crop and climate.

During the falling rate stage (soil limiting) evaporation rate E, was defined as a function of time as

$$E = ct^{1/2} - c(t-1)^{1/2} \tag{2.4}$$

where c = coefficient dependent on soil properties, and t = time.

Transpiration rates were calculated separately from evaporation rates. For plant cover of less than 50 percent, potential transpiration rate, T_p, was calculated as

$$T_p = \alpha_v (1-\tau)(\Delta/(\Delta+\gamma)) R_n \tag{2.5}$$

where Δ = slope of the saturation vapor pressure-temperature curve, γ = psychrometric constant, R_n = net radiation, and $\alpha_v = (\alpha - 0.5)/0.05$. For greater than 50 percent crop cover, T_p was calculated as

$$T_p = (\alpha - \tau)(\Delta/(\Delta+\gamma)) R_n \tag{2.6}$$

This formulation represented transpiration during non-limiting water conditions only. To account for decreasing soil water potential with water content, and effects on transpiration rate, a coefficient of limiting soil water (K_s) was defined by Kanemasu et al. (1976) as

$$K_s = \frac{\Theta_a}{0.3\ \Theta_{max}} \tag{2.7}$$

where Θ_a = average soil water content, and Θ_{max} = water content at field capacity. At water contents above 0.3 Θ_{max}, transpiration rates were assumed to be controlled by climatic conditions only. Ritchie (1973) reported that this model predicted transpiration rates well for sorghum and corn.

In summary, several models for predicting ET rates under both well watered and water stressed conditions are presented. The models presented are all simple approximations of complex dynamic systems. Their simplicity has the advantage of requiring few data inputs, and therefore, they can be applied with relatively few meteorological, soil, or crop measurements taken. However, because of their simplicity, several empirical coefficients are required in each model, and each must be calibrated for specific crops, soil conditions and climatic variables.

Crop Yield Response

Vast literature on this subject revealed yield relationships to water use can range from linear to curvilinear (both concave and convex) response functions (Stegman and Stewart, 1982). These variations are influenced by the type of water parameter that is chosen, its measurement or estimation accuracy, and the varied influences associated with site and production conditions. The following is intended to illustrate the more general relationships of crop yields with water when they are expressed as transpiration, evapotranspiration, or field water supply.

Yield vs. transpiration or evapotranspiration. When yields are transpiration limited, strong correlations usually occur between

cumulative seasonal dry matter and cumulative seasonal transpiration. Hanks (1974) calculated relative yield as a function of relative transpiration:

$$\frac{Y}{Y_p} = \frac{T}{T_p} \tag{2.8}$$

where Y_p = potential yield when transpiration is equal to potential transpiration and Y_p = cumulative transpiration that occurs when soil water does not limit transpiration. With the close correlation between T and ET, dry matter yield vs cumulative ET also plotted as a straight line relationship. Hanks' work demonstrated a physically oriented, simple model to predict yield as a function of water use.

Based on the same idea, an approach which interprets ET or T reduction below potential levels as integrators of the effects of climatic conditions and soil water status on grain yield is used frequently. Such an approach predicts grain yields from physically based models which relate water stresses during various stages of crop growth to final yield, accounting for increased sensitivity to water stress at various stages of growth. Two basic mathematical approaches were taken in the development of these models. One assumed that yield reductions during each crop growth stage were independent. Thus additive mathematical formulations were developed (Moore, 1961; Flinn and Musgrave, 1967; Hiler and Clark, 1971). A second approach assumed interactive effects between crop growth stages. These were formulated as multiplicative models (Hall and Butcher, 1968; Jensen, 1968).

Additive models. The Stress Day Index model is an additive model presented by Hiler and Clark (1971). The model is formulated as

$$\frac{Y}{Y_p} = 1.0 - \frac{A}{Y_p} \sum_{i=1}^{n} (CS_i * SD_i) \qquad (2.9)$$

where A = yield reduction per unit of stress day index, SD_i = stress day factor for crop growth stage i, CS_i = crop susceptibility factor for growth stage i. CS_i expresses the fractional yield reduction resulting from a specific water deficit occurring at a specific growth stage. SD_i expresses the degree of water deficit during a specific growth period.

The stress day index model was utilized to schedule irrigations by calculating the daily SDI value (daily SD * daily CS) and irrigating when it reached a predetermined critical level, SDI. This integrated the effects of soil water deficit, atmospheric stress, rooting density and distribution, and crop sensitivity into plant water stress factor.

Multiplicative models. Jensen (1968) developed the following model

$$\frac{Y}{Y_p} = \prod_{i=1}^{n} \left(\frac{ET}{ET_p} \right)_i^{\lambda_i} \qquad (2.10)$$

where ET/ET_p = relative evapotranspiration rate during the i-th stage of physiological development, and λ_i = crop sensitivity factor due to water stress during the i-th growth stage.

Hill and Hanks (1975) modified the above equation by including factors to account for decreased dry matter production due to planting late season crops, and to account for decreased yields due to excess water. Their equation is

$$\frac{Y}{Y_p} = \prod_{i=1}^{n} \left(\frac{T}{T_p} \right)_i^{\lambda_i} * SYF * LF \qquad (2.11)$$

where $(T/T_p)_i$ = relative total transpiration for growth stage i when soil water is not limiting, SYF = seasonal yield factor which approaches 1.0 for adequate dry matter production, and LF = lodging factor. Because this model relates relative yield to relative transpiration, it is also necessary to predict evaporation rates as a function of ET_p in order to maintain a soil water balance. This yield response model, verified with Missouri soybean experiments, appeared to be an excellent simulator of grain yields as affected by transpiration rates.

Minhas et al. (1974) proposed another multiplicative model expressed as

$$\frac{Y}{Y_p} = \prod_{i=1}^{n} \left\{ 1.0 - \left(\left(1.0 - \frac{ET}{ET_p}\right)^2 \right)_i^{\lambda_i} \right\} \qquad (2.12)$$

where all factors are as previously defined. Howell and Hiler (1975) found that it described adequately the yield response of grain sorghum to water stress.

Yields vs. field water supply. The field water supply (FWS) in irrigated fields is derived from the available soil water at planting (ASWP), the effective growth season rainfall (Re), and the total applied irrigation depth (IRR). Stewart and Hagan (1973) demonstrated that crop yields are related to seasonal ET and seasonal IRR. In a given season, the ASWP and Re components of the seasonal FWS make possible a yield level that is common to both functions. The ET component associated with successive applications of irrigation defines the yield, Y vs ET function above the dryland level, which rises to a Y_{max} - ET_{max} level when the seasonal crop water requirement is fully satisfied. The ET + non-ET components of IRR define a Y vs IRR function of convex form.

That is, non-ET losses increase as water is applied to achieve ET_{max} levels due to the inefficiencies of irrigation methods and the inexactness of water scheduling. The amount of water not used in ET, therefore, represents runoff, deep percolation, and/or residual extractable water in the soil when the crop is harvested. The water management implications of this type of yield function are discussed further in the next sections.

In summary, considerable efforts have been directed toward development of simple models for describing the yield response of crops subjected to water stress conditions. The application of these models to irrigation management appears to be tractable (Hill and Hanks, 1975).

Crop Phenology Model

As a plant goes through its life cycle, various changes occur. Crop ontogeny is the development and course of development of various vegetative and reproductive phases, whereas phenology is the timing of the transition from one phase to the next phase as controlled by environmental factors. To accurately simulate crop growth and yield with biophysical models, crop phenology needs to be successfully predicted (Mishoe et al., in press). Crop parameters needed for growth simulation are closely related to the phenological stages of the plant. These include the duration of leaf area expansion, stem and root growth, as well as the onset and end of pod and seed growth. It is therefore desirable to allow assimilate partitioning values in the model to change as the plant progresses through its reproductive stages.

Currently, many of the practical yield response models have coefficients that depend on crop growth stage (Ahmed et al., 1976;

Childs et al., 1977; Wilkerson et al., 1983; Meyer, 1985). However, in some studies, the crop growth stages have been poorly defined. And most applications of these models use only the mean development times and assume that stochastic variation does not affect the performance of the model. Hence, a systematic approach to define stages relative to physiological development of the crop and to predict these stages under various weather conditions is needed (Boote, 1982). This would lead to more accurate application of yield response models. In the rest of this section, several approaches to modeling phenology are described.

The wide range of controlling factors and crop responses makes phenological modeling challenging. The effect of temperature as well as photoperiod as controlling factors has long been recognized. The concept of thermal time in the form of degree-days is used to account for temperature effect. Degree-days are cumulative daily average air temperature above the base temperature (Prine et al., 1975).

Most models are based on thermal time or photoperiod or a combination of the two. Some models based on thermal time alone are quantitative, based on the analysis of experimental evidence (Kiniry et al., 1983; Tollenaar et al., 1979). Kiniry et al. found that the photoperiod did not affect all of the cultivars of corn. Those that were affected were still insensitive below a threshold photoperiod value of between 10 and 13 hours. For wheat, a quadratic equation, based on day and nighttime temperatures and photoperiod was applied by Robertson (1968), and Doraiswamy and Thompson (1982) to predict the time between phenological stages.

Other models are based on the hypothetical processes involved in crop response (Mishoe et al., 1985; Schwabe and Wimble, 1976). Mishoe

et al. (1985) developed a phenological model based on physiological processes of soybean. One important concept is that a critical period of uninterrupted night length is needed to produce rapid flowering. Also the promotional effect of night length is cumulative. An accumulator (X) value needed to trigger an event is calculated from a function of night length and nighttime temperature. When the cumulative X becomes larger than a threshold level, it triggers the phenological event such as flower initiation. These threshold values for different stages are calibrated from experiments, and are variety dependent.

Incomplete knowledge of biochemical processes involved hampers the development of process models. However, for production management, models using thermal time and night length have successfully predicted phenological events.

Objective Functions

An objective function is a quantitative representation of the decision maker's goal. One may wish to maximize yield, net profit, or water use efficiency. However, these objectives are not equivalent and the use of different objectives may result in different solutions.

Maximizing yield per unit area. This objective may be economically justified when water supplies are readily available and irrigation costs are low. All production practices and inputs must be at yield optimizing levels, and daily cycles of plant water potentials must be managed within limits conducive to maximum seasonal net photosynthesis. From an applied water management viewpoint, this production objective is relatively easy to attain. Many applied experiments (Salter and Goode, 1967) have shown that for many crops,

yields will be near their maximum values when root zone available water is not depleted by more than 25 to 40 percent between irrigations.

Maximizing yield per unit water applied. As irrigation water supplies become more limited or as water costs increase in an area, the management objective may shift to optimizing production per unit of applied water (Hall and Butcher, 1968; Stewart and Hagan, 1973; Howell et al., 1975; Windsor and Chow, 1971). Hiler et al. (1974) have demonstrated that significant improvements in water use efficiency are possible by applying the Stress Day Index method. Stewart et al. (1975) have more recently suggested a simplified management criterion by noting that the maximum yield for a given seasonal ET deficit level tends to occur when deficits are spread as evenly as possible over the growing season. Thus, scheduling is based on the concept of high frequency irrigation, i.e. applying small depths per irrigation at essentially evenly timed intervals.

Maximizing net profit. Applying marginal value vs marginal cost analysis to yield production functions, Stewart and Hagan (1973) were able to determine optimum economic levels of production for maximum water use efficiency, maximum profit under limited water supply, and maximum profit under unlimited water supply, respectively. A problem with this method is that it provides only general guidelines for water management. These guidelines are most applicable to the average or normal climatic conditions in a given region and, therefore, may not apply to specific sites or specific years. In addition the guidelines are seasonal in nature, i.e., they indicate only the seasonal irrigation depth most likely to maximize net profit.

In recent years, numerous models (Dudley et al., 1971; Matanga and Marino, 1979; Bras and Cordova, 1981; Huang et al., 1975) have been developed to address the goal of profit maximization. Methodologies such as dynamic programming are frequently utilized to illustrate how optimal water scheduling or allocation strategies within the growing season can be derived under stochastic conditions.

Risk analysis. Risk assessment of decision alternatives can be approached in several ways. One of the more common approaches is an expected value-variance (E-V) analysis where the decision maker is assumed to maximize utility, where utility is a function of the expected value and associated variance in returns. The specific functional form of this relationship varies by individual depending upon each individual's psychological aversion to risk. For example, the risk averse individuals may be willing to trade a reduction in expected net returns for a decrease in the variance of net returns.

Concerning within-season irrigation strategies, Boggess et al. (1983) expressed the variance of net returns for a particular irrigation strategy as

$$\sigma^2_{\pi i} = \bar{Y}_i^2\, \sigma_p^2 + \bar{P}^2\, \sigma^2_{Y_i} + \bar{\gamma}^2\, \sigma^2_{X_i} + \bar{X}_i^2\, \sigma^2_{\gamma} - 2\sigma_{PY_i,\gamma X_i} \qquad (2.13)$$

where $\sigma^2_{\pi i}$ is the variance in net returns for irrigation strategy i, $\bar{Y}_i$ and $\sigma^2_{Y_i}$ are the mean and variance of yield associated with irrigation strategy i, $\bar{P}$ and σ_p^2 are the mean and variance of crop price, $\bar{\gamma}$ and σ^2_{γ} are the mean and variance of irrigation pumping cost per unit of water, $\bar{X}_i$ and $\sigma^2_{X_i}$ are the mean and variance of irrigation water applied for irrigation strategy i, and $\sigma_{PY_i,\gamma X_i}$ is the covariance between PY_i

and γX_i . Then the relative contribution of each component random variable (price, yield, pumping cost, and irrigation water) to the variance of π was analyzed by normalizing the above equation. Their analysis indicated that irrigating soybeans increased the expected net returns above variable costs and decreased the variability compared to non-irrigated soybeans. Probability curve and convolution of risk techniques were subsequently applied to quantify and interpret the risks associated with alternative irrigation strategies.

Optimization Methods

Systems analysis basically is a problem-solving technique wherein attempts are made to build a replica of a real world system or situation, with the objective of experimenting with the replica to gain some insight into the real world problem. It encompasses several optimization techniques such as dynamic programming, linear programming and simulation. Generally in dealing with irrigation management, dynamic programming techniques are applied to models which are spatially limited to a field of single crop and temporally to one growing season (Hall and Butcher, 1968; Windsor and Chow, 1971; Dudley et al., 1971; Howell et al., 1975; Bras and Cordova, 1981). Linear programming algorithms on the other hand are utilized to analyze farm level cropping patterns models (Windsor and Chow, 1971; Huang et al., 1975; Matanga and Marino, 1979). Simulation is usually used to evaluate specific irrigation policies (Ahmed et al., 1976; Jones and Smajstrla, 1979).

Dynamic programming models. Characteristically, dynamic programming problems are decomposed into stages and decisions are required at each stage. The decision at any stage transforms the system

states and increments the value of the objective function at a particular stage. Changes in the system states may be described by a probability distribution.

In the Howell et al. (1975) dynamic programming formulation, the decision process consisted of whether to irrigate 0., 0.25, 0.5, 0.75, or 1.0 times the potential ET during each of five crop growth stages for grain sorghum. The states consisted of the remaining water to be allocated at each stage and the soil water status, a stochastic state variable. The stochastic state transitions were calculated by utilizing simulation of a soil water balance model.

The solutions produced an optimal sequencing of water application based on expected weather patterns and on differential crop sensitivities to water deficits during each growth stage. The solutions were tabulated. The table provided the stage-by-stage optimal policy. As the season progressed, realizations of rainfall and ET caused the soil water and the remaining water supply to vary from year to year. Therefore, at each stage, the irrigator could update the optimal policy, using the table to optimally allocate water during the remaining part of the growing season.

Bras and Cordova (1981) attempted to solve the same problem by using an analytical approach which included a physical model of a soil-climate system and a stochastic decision-making algorithm. Expressions for the soil water transition probabilities over a given time period and the first two moments of associated actual evapotranspiration were derived analytically. A stochastic dynamic programming algorithm was then used to determine optimal control policies at each irrigation decision point, conditional on the state of the system (soil water content).

Dividing the irrigation season into N stages and taking irrigation depth (I_n) at decision stage n as a decision variable, the objective function (Bras and Cordova, 1981) can be formulated as:

$$B^* = \max_{I \varepsilon \pi} E\left[\sum_{n=1}^{N} R_n^{I_n} \right] - PC \tag{2.14a}$$

where $I = I_1, I_2, \ldots, I_N$

$$R_n^{I_n} = P\, Y_n^{I_n} - \beta\, ID_n^{I_n} - \gamma\, C^{I_n} \tag{2.14b}$$

B^* = maximum net return,

$E[\ ]$ = expectation operator,

PC = production costs different from irrigation costs,

π = feasible set of control policies,

I_n = type of control applied at decision stage n,

N = number of decision stages in the growing season,

$R_n^{I_n}$ = net return by irrigating I_n at decision stage n,

P = price per unit of crop yield,

$Y_n^{I_n}$ = contribution of irrigation decision I_n to actual yield,

β = unit cost of irrigation water,

$ID_n^{I_n}$ = depth of irrigation water associated with operation policy I_n,

γ = fixed cost of irrigation (labor cost), and

$C^{I_n} = 0$, when $ID_n^{I_n} = 0$;

$C^{I_n} = 1$, otherwise.

Since the production cost (excluding irrigation costs), PC, is a constant value, the optimal control law that maximizes the above function will be the same that

$$\underset{I\epsilon\pi}{\text{Max}} \quad E\left[\sum_{n=1}^{N} R_n^{I_n} \right] \tag{2.15}$$

The dynamic programming technique then decomposes this problem into a sequence of simpler maximization problems which are solved over the control space.

<u>Linear programming models</u>. If the objective is to select crops to grow on a farm where water is limiting, linear programming techniques may be applied. Windsor and Chow (1971) described a linear programming model for selecting the area of land to allocate to each crop and the irrigation intensity and type of irrigation system to select. As defined, the set of decision variables, X_{ijkl} represented the number of hectares of crop l to grow in field (or soil type) i, using irrigation practice j, and irrigation system k. The solution would select X_{ijkl} to maximize net profit for the farmer. A required input was net profit associated with X_{ijkl}, C_{ijkl} which included a crop yield response to various conditions. Windsor and Chow used dynamic programming to estimate crop yield response for optimal unit area water allocation.

Their model is designed for decision analysis prior to planting. Their model can also be modified to determine when to plant the crop to take advantage of seasonal rainfall or water availabilities. The within-season scheduling of irrigation on a farm basis (for multiple fields) after crops are planted would require a different formulation. Trava-Manzanilla (1976) presented one example of such a problem.

In the study by Trava-Manzanilla (1976), the objective was to minimize irrigation labor costs in a multi-crop, multi-soil farm subject to constraints on daily water availability, water requirement of the crops and the irrigation method being used. The mathematical formulation of the problem was of zero-one linear integer programming. However, because of the nature of the problem formulation was then transformed to a linear programming model. Two linear programming techniques, Simplex procedure and the Dantzig-Wolfe decomposition principle, were successfully used to resolve the solutions.

Simulation models. Simulation can be used to evaluate specific irrigation policies in an enumerative search for the best policy among those tested. For this approach, models of the soil water status and crop yield responses are required (Ahmed et al., 1976; Jones and Smajstrla, 1979). By defining several explicit, alternate policies and simulating results for one or more crop seasons, crop yields or net returns can be compared for the different policies and the best policy can then be selected. This procedure will not necessarily produce an optimal solution, but from a practical viewpoint, it can provide valuable information to decision makers.

In many of the reported studies (Dudley et al., 1971; Yaron et al., 1973; Minhas et al., 1974; Ahmed et al., 1976), the lack of suitable crop response models was cited as a major limitation. It may not be realistic to estimate crop yield response over a broad range of conditions by empirical approach. Details are needed in the model. Dynamic crop growth models were developed to predict growth and yield of crops using more theoretical considerations and physiological detail (Curry et al., 1975; Childs et al., 1977; Barfield et al., 1977;

Wilkerson et al., 1983). These models are attractive because crop growth stresses, such as those caused by nutrition or pests, can be included, in addition to those caused by water deficits, to provide a more comprehensive tool for crop production management.

However, the crop growth models may have so much detail that they may not be suitable for the problem of long-term production management. Models at other levels of sophistication to describe crop system responses to management practices, such as irrigation, are likely to be more useful. Thus, a general framework for optimization of multiple cropping systems using both optimization and simulation concepts will be developed.

CHAPTER III
METHODOLOGY FOR OPTIMIZING MULTIPLE CROPPING SYSTEMS

Mathematical Model

Several alternative formulations of the multiple cropping problem are studied with regard to their practicality for solutions. These are reviewed, and the most suitable one is described in detail.

Integer Programming Model

Sequencing is concerned with determining the order in which a number of 'jobs' are processed in a 'shop' so that a given objective criterion is optimized (Taha, 1976). In the multiple cropping problem the variable, $X_{ijt_1t_2}$, is defined and equal to one when crop i, variety j, planted at t_1 still grows in the field at time t_2. Otherwise, it is equal to zero. It is also assumed that the growth season for crop i, variety j, planted at t_1 is A_{ijt_1} and the associated net return is C_{ijt_1}. To properly describe the multiple cropping problem, two constraints are considered: only one crop can occupy the field anytime, and a growing season is continuous. Provided with the definition of variables, $X_{ijt_1t_2}$, and constants A_{ijt_1} and C_{ijt_1}, the formulation of an objective function and constraint conditions is

$$\text{Max} \qquad Z = {}_{ijt_1t_2} \; (C_{ijt_1}) \; (X_{ijt_1t_2}) \tag{3.1a}$$

$$\text{s.t.} \qquad {}_{ijt_1t_2} \; X_{ijt_1t_2} \quad T_2 \; , \tag{3.1b}$$

$$_{ijt_1} \; X_{ijt_1t_2} \quad 1 \; , \quad \text{for all } t_2 \; , \tag{3.1c}$$

$$\overset{t_1+A_{ijt_1}}{\underset{t_2=t_1}{}} \; X_{ijt_1t_2} = 0 \quad \text{or}$$

$$\overset{t_1+A_{ijt_1}}{\underset{t_2=t_1}{}} \; X_{ijt_1t_2} = A_{ijt_1}, \quad \text{for all } i,j,t_1, \tag{3.1d}$$

where T_2 is the total number of weeks of an N-year production horizon. The first constraint (3.1b) simply says that a production horizon is of T_2 periods. The second constraint (3.1c) indicates that at any instant of time t_2 only one crop is scheduled to grow in the field. The constraints represented by (3.1d) are imposed to ensure the continuity of a growth season. However, these either-or constraints cannot be implemented directly in a mathematical programming algorithm. To overcome this difficulty, new variables, Y_{ijt_1} are defined. When crop i, variety j, is scheduled for planting at t_1 then $Y_{ijt_1} = 1$. Otherwise, $Y_{ijt_1} = 0$. This problem is then a zero-one integer programming model. The formulation is

$$\text{Max} \quad Z = \sum_{ijt_1} (C_{ijt_1})(Y_{ijt_1}) \tag{3.2a}$$

$$\text{s.t.} \quad \sum_{ijt_1t_2} X_{ijt_1t_2} \leq T_2 , \tag{3.2b}$$

$$\sum_{ijt_1} X_{ijt_1t_2} \leq 1 , \quad \text{for all } t_2 , \tag{3.2c}$$

$$\sum_{t_2=t_1}^{t_1+A_{ijt_1}} (X_{ijt_1t_2})(1 - Y_{ijt_1}) = 0, \quad \text{for all } i,j,t_1, \tag{3.2d}$$

$$\sum_{t_2=t_1}^{t_1+A_{ijt_1}} (X_{ijt_1t_2} - A_{ijt_1})(Y_{ijt_1}) = 0, \quad \text{for all } i,j,t_1, \tag{3.2e}$$

But several difficulties are associated with this formulation. It is noted that the number of X variables in the formulation is equal to $(I * J * T_1 * T_2)$, directly dependent on how often the decision needs to be made. Assume that a decision is to be made every week. For a 4.5-year planning horizon, the total number of X variables is estimated as 4 * 2 * 234 * 234 = 438,048. This cannot be solved economically by the existing integer programming algorithm (Land and Powell, 1979). Moreover, the nonlinear terms in the model should generally result in a computationally difficult problem. Still, the need of constants, C_{ijt_1} and A_{ijt_1}, requires the simulation of as many combinations of (i,j,t_1). Because of all of these shortcomings, the integer programming approach was not pursued further.

Dynamic Programming Model

Because of the nature of dynamic programming techniques which solve a problem by sequential decision-making, the constraint of appearance of a single crop in the field anytime is implicitly coupled in the formulation. In a sense, sequential decision-making provides an interactive mode in the process of solution. When it is required, net return associated with a specific crop candidate is generated and then evaluated. It is very beneficial in terms of storage and computer time requirements.

In a crop production system, management practices consist of irrigation strategy, fertilizer application, pest and disease control, crop rotation, etc. Discrete values assigned to each level of a specific management practice represent the state of a system. For example, percentage of available water in the soil profile (soil water content), is a primary indicator for irrigation management. Under an unlimited water supply situation, without losing generality, (C,W,N) are chosen as state variables to identify state transition in the optimization model, where C stands for the preceding crop, W for soil water content, and N for soil nutrient level.

The inclusion of nutrient level (N) in the formulation is to express the potential application to other areas of interest. Nonetheless, irrigation policy is solely emphasized in the iterative functional equation, because this framework is to be demonstrated with the application to irrigation management.

The dynamic programming model of multiple cropping is formed as follows. First, the optimal value function F(C,W,N,t) is defined as

$F(C,W,N,t)$ = maximum return obtainable for the remainder t periods, starting with the current state (C,W,N). (3.3)

In terms of these symbols, Bellman's principle of optimality gives the recurrence relation,

$$F(C_1,W_i,N_i,t) = \max_{C_2 \in S(C_1,t)} R^*(C_2,I^*,t) + F(C_2,W_f,N_f,t-a(C_2)) \quad (3.4)$$

where W_i = state of soil water at the beginning of the season,

W_f = state of soil water at the end of the season,

N_i = value of nutrient level at the start of the season,

N_f = value of nutrient level at the end of the season,

C_1 = preceeding crop,

C_2 = selected crop, decision variable,

$S(C_1,t)$ = proper subset of crop candidates dependent on C_1 and season t, due to practical considerations of crop production system,

$a(C_2)$ = growth season of crop C_2,

I^* = optimal realization of irrigation policies, a vector $(I_1^*, I_2^*, \ldots I_k^*)$ represents the depths of irrigation water associated with individual operations,

R^* = maximum return obtained from growing crop C_2 by applying optimal irrigation policy I^*.

The state transition from the start of a season to the end of a season is determined by the system equations:

$$W_f = g\ (C_2,\ I^*,\ W_i), \tag{3.5a}$$

$$N_f = h\ (C_2,\ I^*,\ W_i,\ N_i). \tag{3.5b}$$

These functions are not explicitly expressible. It is not realistic to represent the complicated soil-plant-atmosphere continuum in terms of simple functional relationships. Simulation models may be employed to carry out state transitions.

In order to use the iterative functional equation, it is necessary to specify a set of boundary conditions to initialize the computational procedure. Because the functional equation expresses the optimal value function at t in terms of the optimal value function at $(t - a(C_2))$, the boundary conditions must be specified at the final stage $t = 0$. Formally, the appropriate boundary conditions are

$$\begin{aligned} F(C,W,N,t) &= \ \ 0, \text{ when } t = 0 \\ F(C,W,N,t) &= -\infty, \text{ when } t < 0 \\ &\qquad \text{for every } C,W,N. \end{aligned} \tag{3.6}$$

In addition, an optimal policy function, the rule that associates the best first decision with each subprogram, is needed to recover the optimal decision for the original whole problem. The optimal policy function in the problem is defined as

$$P(C_1,\ W_i,\ N_i,\ t) = (C_2,\ W_f,\ N_f,\ a(C_2)) \tag{3.7}$$

where W_f = soil water status at end of a season, N_f = nutrient level at end of a season, C_2 = index of the selected crop, $a(C_2)$ = growing season of C_2 .

Starting with the boundary conditions, the iterative functional equation is used to determine concurrently the optimal value and policy functions backward. When the optimal value and decision are known for the initial condition, the solution is complete and the best cropping sequence can be traced out using the optimal policy function. Namely, the optimal solution is $F^*(C_0, W_0, N_0, T)$, where T = the span of N-year growing period, (C_0, W_0, N_0) is the initial condition in which production plan is to be projected.

However, it is not very clear whether certain states (C, W, N, t) are relevant to the possible optimal system. Total enumerations of optimal value functions F(C, W, N, t) are required to resolve the optimal solution $F^*(C_0, W_0, N_0, T)$. In terms of computational efficiency, this dynamic programming model is not very appealing. Therefore, a more comprehensive, efficient model needs to be investigated.

Activity Network Model

Selecting crop sequences to optimize multiple cropping systems can be formulated as an activity network model. In a network, a node stands for an event or a decision point. An activity, represented by an arc, transfers one node to another. In this particular application to irrigation management, nodes represent discrete soil water contents at every decision period. Arcs, not necessarily connecting with adjacent nodes, have lengths that denote net returns associated with the choice of crop and irrigation strategy. The structure of the network is demonstrated in Figure 1, where C_i is crop variety i and S_j is irrigation stragegy j. The S and T nodes are dummy nodes, representing the source and terminal nodes of the network, respectively.

As noted in Figure 1, all arcs point in one direction from left to right. There is no cycle in this network. This feature will prove advantageous in developing a simplified algorithm for network optimization. While circles are all potential decision nodes, solid-line ones are actual decision nodes which are generated by system simulations, and dashed-line circles are fictitious, not accessible to other nodes. In the dynamic programming model, these inaccessible nodes are not detectable so that efforts on computing optimal values for dashed-line nodes are wasted. In contrast, the inaccessible nodes are detectable in the activity network model and more efficient computation is accomplished. Under different weather conditions, networks of a multiple cropping system vary.

In designing multiple cropping systems, several principles verified by field experiments should be considered. These are: an idle period may be required to restore the soil water reservoir, or to alleviate pest population or chemical residues; consecutive scheduling of the same crop may require more intensive management; and genetic traits may prohibit planting certain varieties in some season of a year. Some of these system criteria can be incorporated into simulation to generate a multiple cropping network. Other aspects of the system (i.e. improper consecutive scheduling of the same crop) restricted by model representation may be reconsidered by a post-optimization scheme. In such a manner, a more realistic system network is considered for obtaining optimal crop scheduling.

The objective of optimizing multiple cropping systems is defined to maximize total net return over a specified long-term period. In network analysis terminology, it is to seek the 'longest path' of a network.

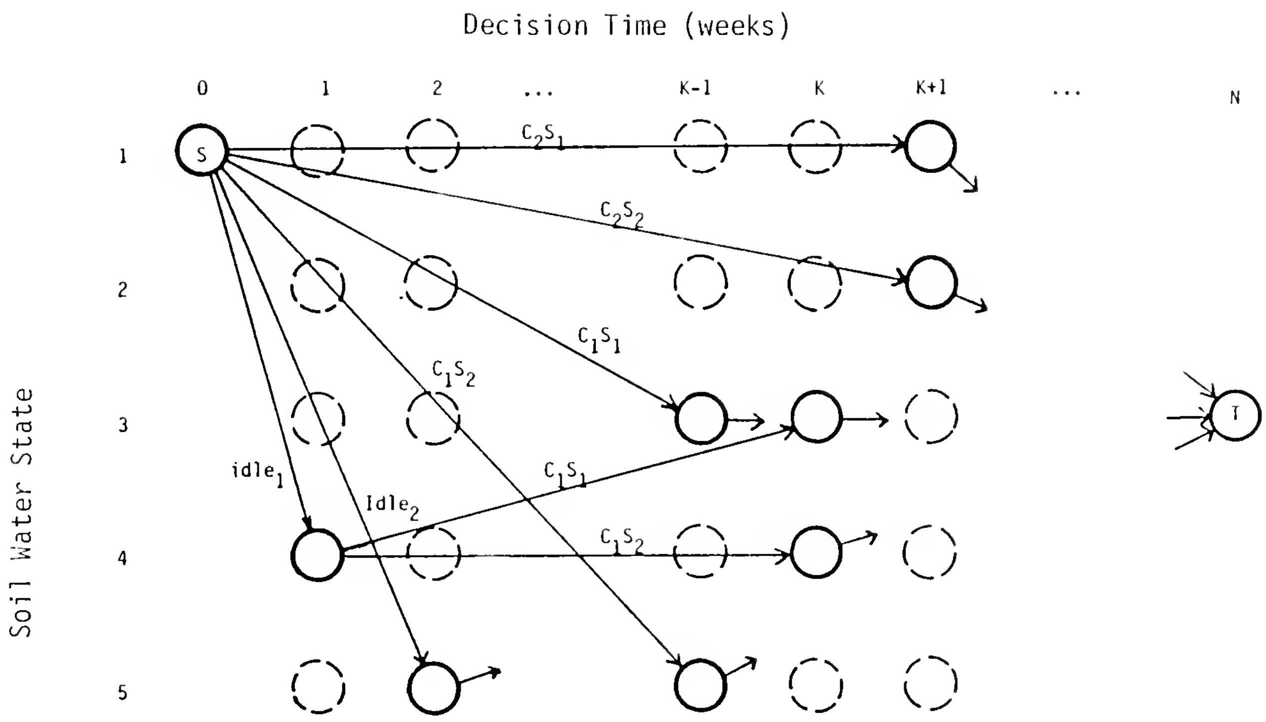


Figure 1. A system network for multiple cropping.

Since devaluation of cash value needs to be taken into consideration in a long-term production horizon, total discounted net return of future profits is to be maximized in the study.

A longest path solution algorithm can be expanded to search for the K longest paths from the start node to terminal node. Determining the K longest paths provides useful information for system analysis. The advantages are as follows: First, such information provides a means of assessing the sensitivity of the optimal solution to possible suboptimal decisions. Second, one may be interested in a class of solutions and not just in a single solution. Third, the K longest paths provide a measure of the robustness of the underlying model when the data are approximate. Moreover, in case post optimization analyses are necessary to impose additional constraints on good solution paths in a system network, calculation of the K longest paths provides a means of efficient computation.

As described, an arc length in a multiple cropping system network represents the return resulting from an optimal, single crop production season. This represents a second-level optimization problem, which is referred to as within-season management, i.e. optimal irrigation scheduling. The problem of temporal water allocation in an irrigated field consists of deciding when and how much water to apply in order to maximize net returns. This problem is complicated by the uncertainty of weather and by the fact that many crops exhibit critical growth stages during which the crop sensitivity to soil water stress is high.

Systems analysis techniques such as simulation and dynamic programming have been used in the past to determine the optimal operation policies in an irrigation system. The necessity of

implementation of more dynamic, detailed crop phenology and growth/yield models makes mathematical programming impractical. Simulation therefore is required to evaluate within-season management strategies. As a result, the activity network model coupled with the simulation-optimization techniques provides a framework for optimizing multiple cropping systems by selecting crop sequence and determining optimal within-season management practices.

Thus, methodology is developed and summarized as follows:

1. To provide base data, models for simulating crop growth and yield are constructed.
2. Considering systems options and constraints, a realistic multiple cropping network is generated.
3. Applying the longest path algorithm, the K longest paths are solved to evaluate various cropping sequences.

Crop-Soil Simulation Model

The crop-soil simulation model serves two purposes in optimizing multiple cropping systems. First, the simulation is necessary to define the state transitions (i.e. soil water contents) in the previously discussed mathematical model. Secondly, simulation is an approach to study irrigation management strategies. The problem of optimally distributing irrigation water over the growing season is difficult primarily because of imperfect knowledge of rainfall distribution over the season. In addition, uncertainty in the distribution of other weather variables which affect crop yields complicates the optimization problem.

In general, uncertainty in the time distribution of inputs or resources to a process which is to be optimized can be treated using some form of stochastic programming, the inputs as random variables, and the objective function to be optimized as some fairly simple production function of inputs. Unfortunately, the complex nature of crop production lends itself to simple production functions only in a general statistical sense. In order to investigate the effects of irrigation decisions at different points within the growing season, a detailed simulation model is useful.

Such a simulation model is intended to integrate the effects of weather variables and irrigation schedules on crop growth. It simulates the progress of a crop during the time in which it interacts with its environment. As the crop grows from day to day and uses the water stored in the root zone, water deficits develop and are counter-balanced by irrigation or rainfall. This closed loop simulation describes the frequency and duration of water deficits that affect evapotranspiration and crop yield. By imposing a series of alternate irrigation strategies on the simulation model, one can evaluate the effect on yield of various strategies. To find the optimal solution, ranking the estimated net return gives the most efficient strategy for a given specific weather pattern.

As discussed by Jones and Smajstrla (1979), simulation models at different levels of sophistication have been developed to study the problem. In this work, a crop yield response model is included with the soil water balance model so that irrigation strategy for maximizing net return can be studied. The soil water balance model is primarily used to provide the necessary data (daily ET) for describing the yield

response of the crop by the yield model. In addition, a crop phenology model is coupled to systematically predict growth stage relative to physiological development of the crop. In so doing, different levels of water use of the crop at various growth stages can be realistically simulated, and more accurate estimation of yield is possible. These models are described in detail below.

Crop Phenology Model

Corn and peanut phenology. For corn and peanut, heat units are used to predict physiological development. In the model, the physiological day approach, a modification of the degree-day method is used. Because the units of degree-day are products of temperature and time, it is convenient to express the accumulation in units of physiological time. To accomplish this, the degree-day unit is normalized with respect to a given temperature, 30 C^{o}. The physiological days are calculated as follows.

$$
\begin{aligned}
PD &= 0 && \text{for } T < 7, \\
PD &= \sum_{i=1}^{n} \frac{T(\Delta t_i) - 7}{30 - 7} \Delta t_i && \text{for } 7 \leq T < 30, \qquad (3.8) \\
PD &= \sum_{i=1}^{n} \frac{45 - T(\Delta t_i)}{45 - 30} \Delta t_i && \text{for } 30 \leq T < 45, \\
PD &= 0 && \text{for } T \geq 45,
\end{aligned}
$$

where PD = physiological day, $T(\Delta t_i)$ = temperature in the time interval Δt_i . Physiological days accumulate until specific thresholds are reached. Stages occur at the thresholds the stages are said to be set. In this study, the crop season is divided into four stages. For corn and peanut, stages of growth and threshold values of physiological development are shown in Table 1.

Wheat phenology. For wheat, four stages, planting to late tillering, late tillering to booting, heading to flowering, and grain filling are used to characterize the wheat life cycle. Time between phenological stages is predicted by using the Robertson model (1968). The approach uses the multiplicative effects of temperature and daylength to determine time between events. In the model, the average daily rate ΔX of development is calculated as

$$\Delta X = \left(a_1(L-a_o) + a_2(L-a_o)^2\right) \left(b_1(T_1-b_o) + b_2(T_1-b_o)^2 + b_3(T_2-b_o) + b_4(T_2-b_o)^2\right) \tag{3.9}$$

where L = daily photoperiod,

T_1 = daily maximum (daytime) temperature,

T_2 = daily minimum (nighttime) temperature.

And a_o, a_1, a_2, b_o, b_1, etc. are characteristic coefficients of specific stages. Values of these coefficients are shown in Table 2. A new stage (S_2) is initiated when the summation

$$XM = \sum_{S_1}^{S_2} \Delta X = 1 . \tag{3.10}$$

Table 1. Threshold values for physiological stages of growth of corn and peanut.

Crop	Stage of Growth	Threshold Values of Phenological Development (Physiological Days)	Source
Full season corn	Planting to silking	38.7	Bennett (personal communication)
	Silking to blister	45.1	
	Blister to early soft dough	66.3	
	Early soft dough to maturity	81.4	
Short season corn	Planting to silking	33.6	Agronomy Facts, 1983
	Silking to blister	40.7	
	Blister to early soft dough	57.7	
	Early soft dough to maturity	70.4	
Peanut	Planting to beginning flowering	27.3	Boote, 1982
	Beginning flowering to a full pod set	42.4	
	A full pod set to beginning maturity	68.2	
	Beginning maturity to harvest maturity	97.3	

Table 2. Coefficients of a multiplicative model for predicting wheat phenological stages (Robertson, 1968).

Coefficients	Phenological Stage				
	Planting to Emergence	Emergence to Late Tillering	Late Tillering to Booting	Heading to Flowering	Grain Filling
a_0	**	8.413	10.93	10.94	24.38
a_1	**	1.005	0.9256	1.389	-1.140
a_2	**	0.0	-0.06025	-0.08191	0.0
b_0	44.37	43.64	42.65	42.18	37.67
b_1	0.01086	0.003512	0.002958	0.0002458	0.00006733
b_2	-0.000223	-0.00000503	0.0	0.0	0.0
b_3	0.009732	0.0003666	0.003943	0.0003109	0.00003442
b_4	-0.000227	-0.00000428	0.0	0.0	0.0

** In this early stage, growth is independent of daily photoperiod.

The summation (XM) is carried out daily from one phenological stage S_1 to another S_2.

Primarily, five growth stages and centigrade temperatures were used in the Robertson model. Modification by combining stages 1 and 2 into a single stage has been made to accommodate to the study.

Soybean phenology. The model of soybean phenology, developed by Mishoe et al. (in press) and implemented by Wilkerson et al. (1985) is complicated. A version of the model was adapted for the study. The model uses cultivar specific parameters, night length, and temperatures to generate physiological development. The development phases of soybean are described in Table 3. Some phases of development are dependent on night length and temperature whereas others are dependent only on temperature.

Temperature effect on development is expressed as physiological time. Physiological time is calculated as the cumulative sum of rates of development, starting at the beginning of a phase. The end of a phase occurs when the cumulative physiological time reaches the threshold as indicated in Table 3.

A nighttime accumulator is used to represent photoperiod effects on development. The nighttime accumulator of the model is represented as follows:

$$X_m = \sum TF * NTA \qquad (3.11)$$

where X_m = the accumulator value to trigger an event,

TF = temperature factor computed using the function shown in Figure 2,

NTA = night time accumulator function shown in Figure 3.

Table 3. Description and threshold values of phenological stages and phases for soybean cultivars (Wilkerson et al., 1985).

Growth Stage	Description	Phase	Threshold 'Bragg'	Threshold 'Wayne'
I	Physiological time from planting to emergence	1	6.522	6.522
	Physiological time from planting to unifoliate	2	10.87	10.87
	Physiological time from unifoliate to the end of juvenile phase	3	2.40	2.40
	Photoperiod accumulator from the end of juvenile phase to floral induction	4	1.00	1.00
II	Physiological time from floral induction to flower appearance	5	9.48	9.48
	Photoperiod accumulator from flowering to first pod set	6	0.14	0.20
	Photoperiod accumulator from flowering to R-4	7	3.0	6.0
III	Photoperiod accumulator from flowering to the last V-stage	8	0.16	0.5
	Photoperiod accumulator from flowering to the last possible flowering date	9	0.575	0.6
IV	Photoperiod accumulator from flowering to R-7	10	20.35	14.5
	Physiological time from R-7 to R-8	11	12.13	10.0

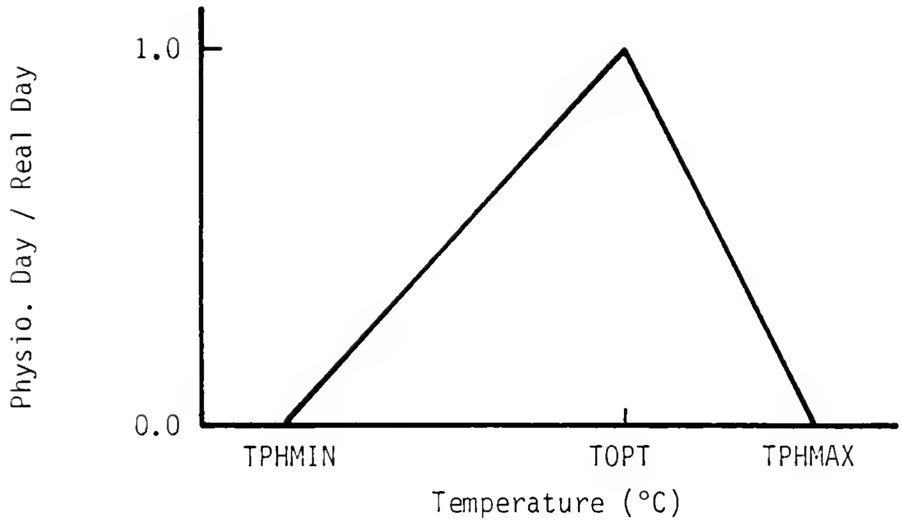


Figure 2. Rate of development of soybean as a function of temperature.

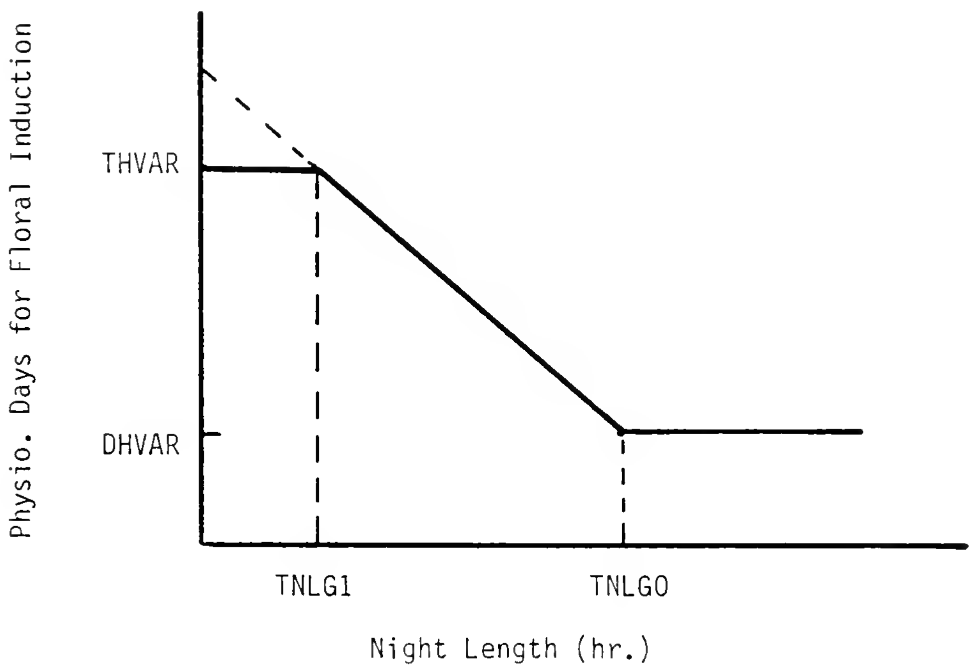


Figure 3. Effect of night length on the rate of soybean development.

Figure 2 is the normalized function to calculate physiological time. In Figure 2, data used for minimum, optimal and maximum temperatures were 7, 30, 45^{o}C, respectively. Figure 3 shows the relationship between night length and physiological days to development based on phase 4, the floral induction phase. Because the threshold for development for phase 4 was defined to be a constant (1.0), the relationship varied with cultivars in Figure 3. The values for this relationship of 'Bragg' and 'Wayne' soybean shown in Table 4 were taken from Wilkerson et al. (1985). Based on these calibrated curves, thresholds (Table 3) for other photoperiod phases also vary among cultivars.

The amount of development during one night is calculated by multiplying the average temperature for the nighttime by the inverse of days to development at a given night length. The function (equation 3.10) is accumulated using a daily time step. When the prescribed threshold is reached, the event is triggered and the crop passes into the next stage.

Crop Yield Response Model

Crop growth is closely correlated to evapotranspiration (ET). Based on this principle, yield response models which interpret ET reduction below potential levels as integrators of the effects of climatic conditions and soil water status on grain yield were developed. To account for increased sensitivity to water stress at various stages of growth, and the interactive effects between crop growth stages, the Jensen (1968) multiplicative form

$$Y/Y_p = (ET_1/ET_{p1})^{\lambda_1} (ET_2/ET_{p2})^{\lambda_2} (ET_3/ET_{p3})^{\lambda_3} (ET_4/ET_{p4})^{\lambda_4} \qquad (3.12)$$

is used, where potential yield, Y_p, is varied as a function of planting dates. Maximum yield factors that reduce yield of each crop below its maximum value as a function of planting day for well-irrigated conditions are shown in Figure 4. The length of each stage is predicted by the use of crop phenology model.

To obtain crop sensitivity factors (λ_i) to water stress, intensive literature studies have been made. Boggess et al. (1981), based on many simulations from SOYGRO were able to quantify these factors (shown in Table 5) by statistical analysis. Smajstrla et al. (1982) also estimated λ_i for soybean in a lysimeter study, and their estimates of λ_i were similar to those found by Boggess et al. (1981). For corn and peanut, attempts have been made without success to obtain the factors from a series of experimental studies (Hammond, 1981). The factors used in Table 5 were derived from FAO publication (Doorenbos, 1979). For wheat, no data were available for Florida conditions. Therefore, an experiment on wheat to be described in the later chapter was performed to obtain λ_i and related crop response to irrigation practices.

Soil Water Balance Model

In order to predict ET rates under well-watered and water stressed conditions, a soil water balance model was developed to integrate existing knowledge about crop water use, weather patterns, and soil properties into a framework compatible with irrigation objectives. A model previously described by Swaney et al. (1983) was adapted for this study.

Table 4. Values of the parameters for the nighttime accumulator function of the soybean phenology model (Wilkerson et al., 1985).

Name of Parameters	Value of The Parameters	
	'Bragg'	'Wayne'
THVAR (day)	63.0	32.0
DHVAR (day)	2.0	2.0
TNLG1 (hour)	5.2	5.2
TNLG0 (hour)	11.0	9.5

Table 5. Crop sensitivity factors, λ_i, for use in the simulation.

	Crop Sensitivity Factors				
Crop	Stage 1	Stage 2	Stage 3	Stage 4	Source
Corn	0.371	2.021	1.992	0.475	Doorenbos (1979)
Soybean	0.698	0.961	1.034	0.690	Boggess et al. (1981)
Peanut	0.578	1.032	1.531	0.772	Doorenbos (1979)
Wheat	0.065	0.410	0.114	0.026	Personal observation

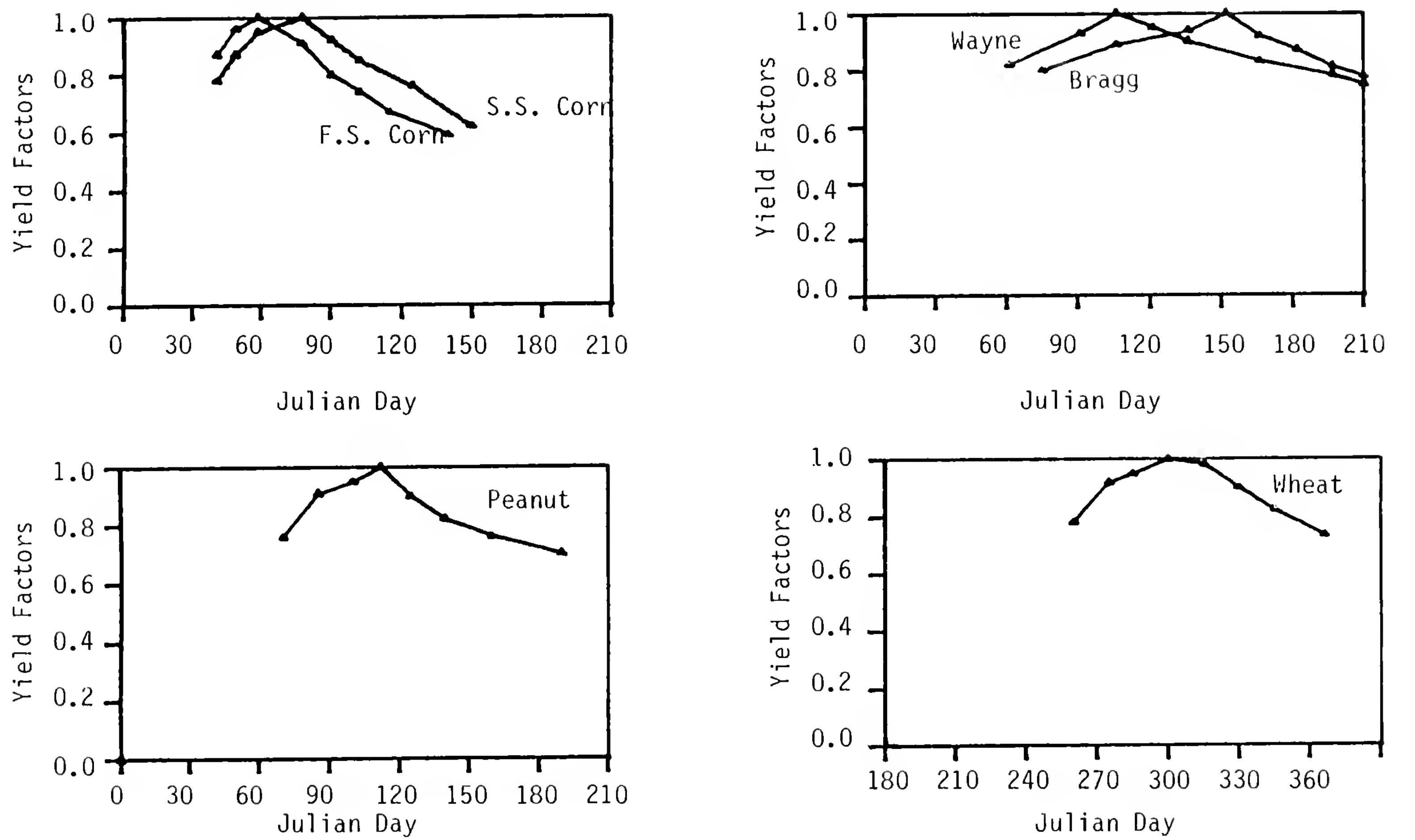


Figure 4. Maximum yield factors that reduce yield of each crop below its maximum value as a function of planting day for well-irrigated conditions.

The soil water balance model divides the soil into two zones: an evaporation zone in the uppermost 10 cm of the soil, and a root zone of variable depth underneath. This shallow evaporation zone is selected for the sandy soil used in the model, and would not be sufficient for heavier soils. Root zone depth is increased during the season by simulating root growth. Under well-irrigated conditions, rooting depth of the crop as a function of time is shown in Figure 5. The soil used is characterized by its field capacity and permanent wilting point.

Evaporative water loss is removed from the evaporation zone and transpiration water is lost from both zones depending on their respective water contents. Due to the high infiltration rates of the sandy soil, all rainfall is added to the profile until field capacity is reached, and excess water is assumed to drain from the profile. When the fraction of available soil water reaches a critical level of a pre-determined irrigation strategy, irrigation water is applied and treated as rainfall. If both rainfall and irrigation occur on the same day, the effect is additive.

The soil water balance model requires daily rainfall and potential evapotranspiration (ET_p), which is estimated by a modified version of the Penman equation. The ET_p is then used to calculate potential transpiration (T_p) using a function of leaf area index (Ritchie, 1972):

$$T_p = 0 \qquad L_{ai} < 0.1 \qquad (3.13a)$$

$$T_p = ET_p(0.7 * (L_{ai})^{1/2} - 0.21) \qquad 0.1 \leq L_{ai} \leq 3.0 \qquad (3.13b)$$

$$T_p = ET_p \qquad 3.0 < L_{ai} \qquad (3.13c)$$

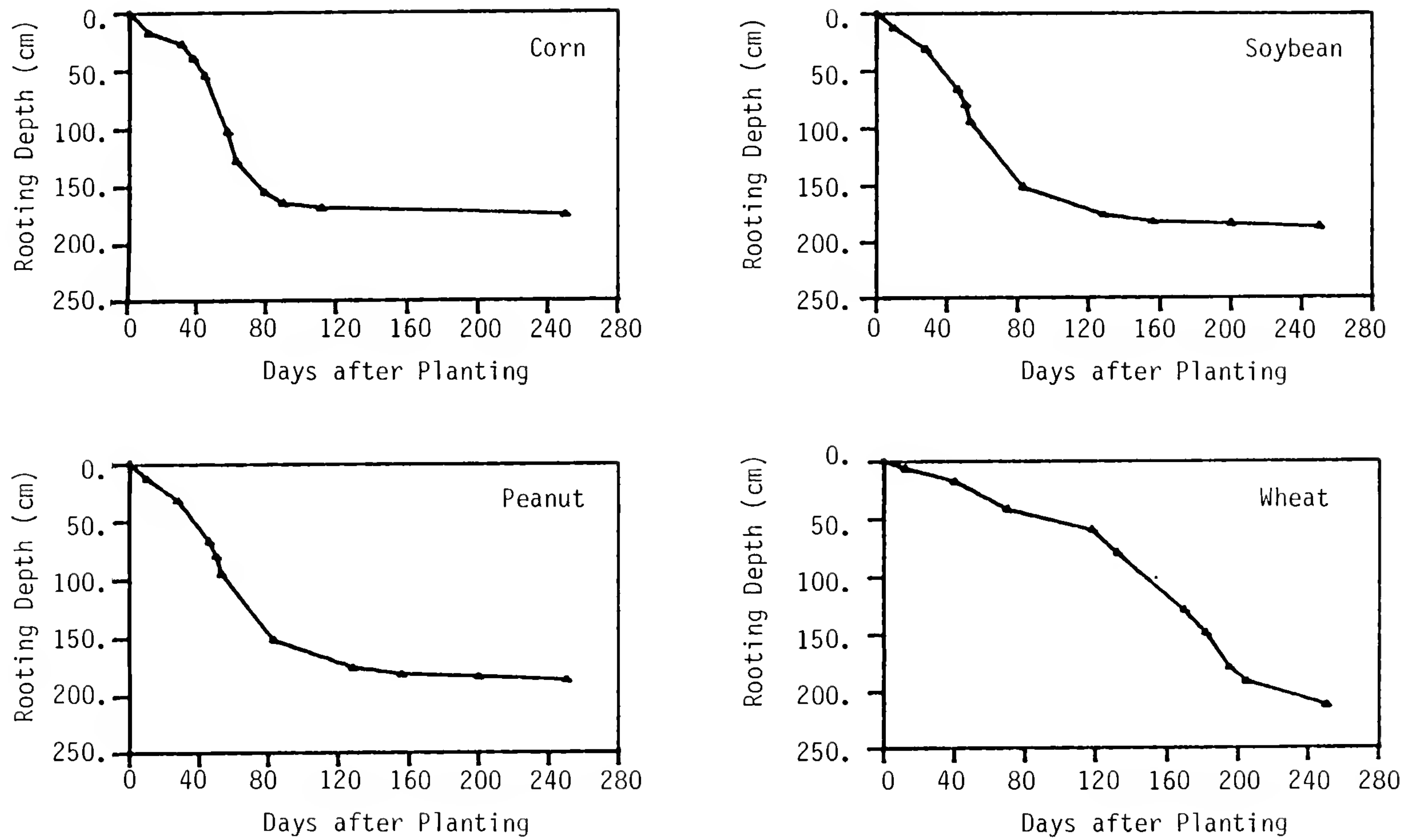


Figure 5. Crop rooting depth after planting under well-irrigated conditions.

where L_{ai} = leaf area index. For well-irrigated crops, leaf area index functions as seasons progress are shown in Figure 6.

Values of actual evaporation (E) and transpiration (T) limited by available water in the two soil zones are calculated from potential values using time from the last rainfall in the case of E, and a soil water stress threshold (Θ_c') in the case of T. Calculation of transpiration is as follows:

$$T = T_p \qquad \Theta' \geq \Theta_c' \tag{3.14a}$$

$$T = T_p * (\Theta'/\Theta_c') \qquad \Theta' < \Theta_c' \tag{3.14b}$$

where Θ' = ratio of soil water in root zone, as a fraction of field capacity, $\Theta' = (\Theta_r - \Theta_d) / (\Theta_{fc} - \Theta_d)$,

Θ_c' = critical value of Θ' below which water stress occurs and transpiration is reduced, various values are used for different growth stages and crops,

Θ_r = volumetric water content of root zone,

Θ_d = lower limit of volumetric water content for plant growth,

Θ_{fc} = field capacity of the soil.

Two stages of evaporation from soil are implemented. In the constant rate stage (immediately following rainfall event or irrigation), the soil is sufficiently wet for the water to be evaporated at a rate

$$E = \mathrm{Min}\ (E_p,\ W_e) \tag{3.15}$$

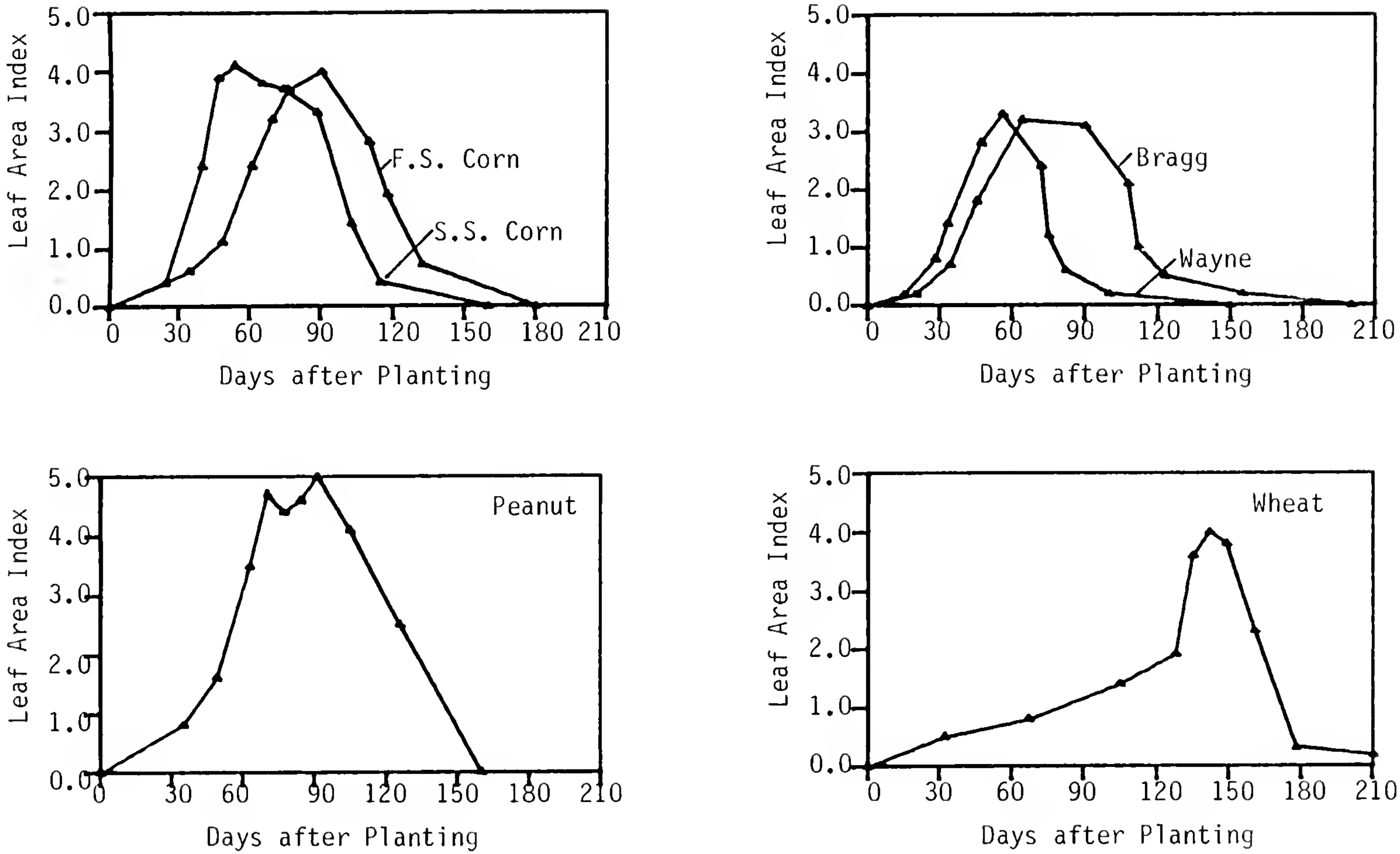


Figure 6. Leaf area index for well-irrigated crops as a function of time.

where W_e = volume of water in the evaporation zone (cm), E_p = potential evaporation below the canopy. In the falling rate stage (stage 2), evaporation is more dependent on the hydraulic properties of soil and less dependent on the available atmosphere energy. For each subsequent day, the daily evaporation rate is obtained by (Ritchie, 1972)

$$E = \text{Min}\ \{\ (\alpha t^{1/2} - \alpha(t-1)^{1/2}),\ W_e\} \tag{3.16}$$

where α is a constant dependent on soil hydraulic properties. For sandy soil, $\alpha = 0.334$ cm day$^{-1/2}$.

For practical application, the Penman equation is considered the most accurate method available for estimating daily ET. The Penman formula for potential evapotranspiration is based on four major climatic factors: net radiation, air temperature, wind speed, and vapor pressure deficit. As summarized by Jones et al. (1984), the potential ET for each day can be expressed as

$$ET_p = \frac{\Delta R_n/\lambda + \gamma E_a}{\Delta + \gamma} \tag{3.17}$$

where ET_p = daily potential evapotranspiration, mm/day

Δ = slope of saturated vapor pressure curve of air, mb/^{o}C

R_n = net radiation, cal/cm^2 day

λ = latent heat of vaporization of water, 59.59-0.055 T_{avg} cal/cm^2 mm or about 58 cal/cm^2 mm at 29^{o}C

E_a = $0.263(e_a - e_d)\ (0.5 + 0.0062u_2)$

e_a = vapor pressure of air = $(e_{max} + e_{min})$ / 2, mb

e_d = vapor pressure at dewpoint temperature T_d (for practical purposes $T_d = T_{min}$), mb

u_2 = wind speed at a height of 2 meters, Km/day

γ = psychrometric constant = 0.66 mb/^oC

e_{max} = maximum vapor pressure of air during a day, mb

e_{min} = minimum vapor pressure of air during a day, mb.

Saturated air vapor pressure as a function of air temperature, $e^*(T)$, and the slope of the saturated vapor pressure-temperature function, Δ are computed as follows:

$$e^*(T) = 33.8639\{(.00738T + .8072)^8 - .000019(1.8T + 48) + .001316\} \tag{3.18}$$

$$\Delta = 33.8639\{0.05904(0.00738T + 0.8072)^7 - 0.0000342\} \tag{3.19}$$

In general, net radiation values are not available and must be estimated from total incoming solar radiation, R_s , and the outgoing thermal long wave radiation, R_b. Penman (1948) proposed a relationship of the form

$$R_n = (1-\alpha)\ R_s - R_b \tag{3.20}$$

where R_n = net radiation in cal/cm^2 day,

R_s = total incoming solar radiation, cal/cm^2 day

R_b = net outgoing thermal long wave radiation,

α = albedo or reflectivity of surface for R_s.

Albedo value α is calculated for a developing canopy on the basis of the leaf area index, L_{ai}, from an empirical equation (Ritchie, 1972),

$$\alpha = \alpha_s + 0.25\ (a - \alpha_s)\ L_{ai} \qquad (3.21)$$

where α_s is average albedo for bare soil and α for a full canopy is a. And an estimate of R_b is found by the relationship:

$$R_b = \sigma T^4(0.56 - 0.08\sqrt{e_d})\ (1.42R_s/R_{so} - 0.42) \qquad (3.22)$$

where σ = Stefan-Boltzmann constant ($11.71*10^{-8}$ cal/cm^2 day/^{o}K),

T = average air temperature in ^{o}K (^{o}C + 273),

R_{so}= total daily cloudless sky radiation.

Values of R_s are available from weather stations in Florida. Clear-sky insolation (R_{so}) at the surface of the earth though needs to be estimated. The equation (3.16), along with the discussed procedures for estimating variables, is then used to calculate potential ET from a vegetated surface.

The calculation of potential evaporation below the canopy, E_p, is essential to predict soil evaporation when the surface is freely evaporating. Proposed by Ritchie (1972), E_p is calculated as follows:

$$E_p = (\Delta/(\Delta + \gamma))R_n \qquad (3.23)$$

where R_n is net radiation at soil surface.

Irrigation Strategy

In order to study irrigation decisions, irrigation options input by the user are available to the simulation model. The irrigation strategies take the following form. The grower will irrigate on any day of the season, if the water content in the root zone of the soil is depleted to the threshold value (70% of availability by volume) specified by the strategy. If the condition is met, irrigation water is applied in an amount specified by the user. Frequent irrigation applying less water per application (1 cm) is used in the model. On the other hand, the rain-fed strategy depends totally upon rainfall.

Model Implementation

In order to study multiple cropping systems as well as associated management strategies, models are needed to summarize and operationalize knowledge about plant growth, yield, weather patterns, soil properties and economics into a framework compatible with system objectives. Therefore, computer programs were written in FORTRAN 77 to evaluate the methodology. Figure 7 shows a schematic diagram for the methodology. As outlined in the previous section of mathematical model, in order to optimize multiple cropping systems, three independent steps, system description, generation of network, and network optimization are essential. Detailed descriptions and source code of subroutines to execute the methodology are given in appendix A. The purpose of this section is to provide discussions on model implementation in general.

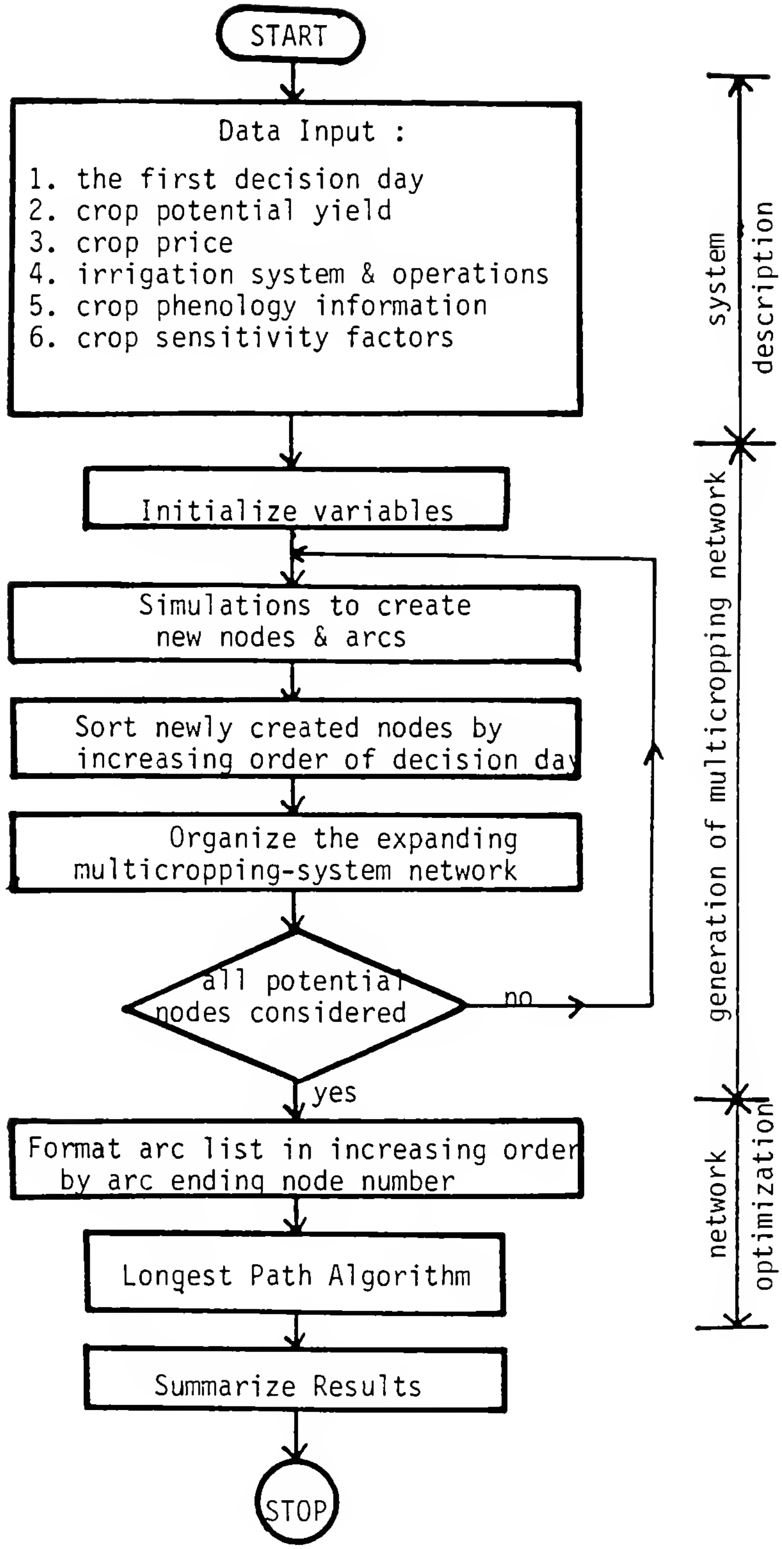


Figure 7. A schematic diagram for optimal sequencing of multiple cropping systems.

Network Generation Procedures

As discussed, nodes of a system network are specified by their time coordinate and their system states. In this particular application, it is proper to use a weekly decision interval. For limited water retaining capacity of sandy soil, soil water contents as state variable are discretized by an 1% interval between field capacity (10%) and permanent wilting point (5%). Hence, there are a total of 6 states of the system.

Net profit is gross receipts from crop sale minus total variable cost. The variable cost for crop production is calculated by the collective cost of production excluding irrigation plus variable cost of seasonal irrigation. In planning of longterm production, devaluation of cash value needs to be taken into consideration. Assume current depreciation rate is i (12%). Present value of a future sum (F) is calculated as

$$P = F / (1 + i)^n \tag{3.24}$$

where n is the year when F occurs. When F will be the net return of future crop production, P is then the discounted net return evaluated at the planning time.

In order to have a multiple cropping system network, simulation techniques are applied. The tasks of these simulations are to keep track of soil water status daily in order to be compatible with irrigation objectives, to project the next crop and its planting date (new nodes), and to estimate returns (arc lengths) related to the decisions.

In the simulation, a crop season includes a one-week period to allow for land preparation, and one week to allow for the harvesting operation. Once a crop and irrigation strategy are decided, phenology and soil water balance models are used every day to simulate the states of the system. After all simulations of one single season for different crops and irrigation strategies are performed, several new nodes for the next crop are generated and new arcs are extended. In simulations, the limitations on planting seasons of specific crops are shown in Figure 8 (personal communication with extension agent, D.L. Wright). Yield also depends on the time during each interval when planting occurs.

In the process of optimizing a network, it is advantageous to have a network whose nodes are sequentially numbered from a source node to a terminal node. Since a straightforward simulation procedure does not result in such a sequentially ordered network. It is necessary to re-number a currently existing network when expanding the network by extending arcs from the presently considered node to new nodes generated by simulations. Therefore, a procedure composed of appending, inserting and re-numbering nodes are required in order to have an ordered network.

At each node (present planting day), a combination process of simulation and re-numbering is performed. The process continues to expand a network until the end of a planning horizon. As a result, a multiple cropping system network whose nodes are sequentially numbered is generated and ready for optimization.

Network Optimization

The optimization algorithm to seek K longest, distinct path lengths of a network of multiple cropping system is discussed herein. For

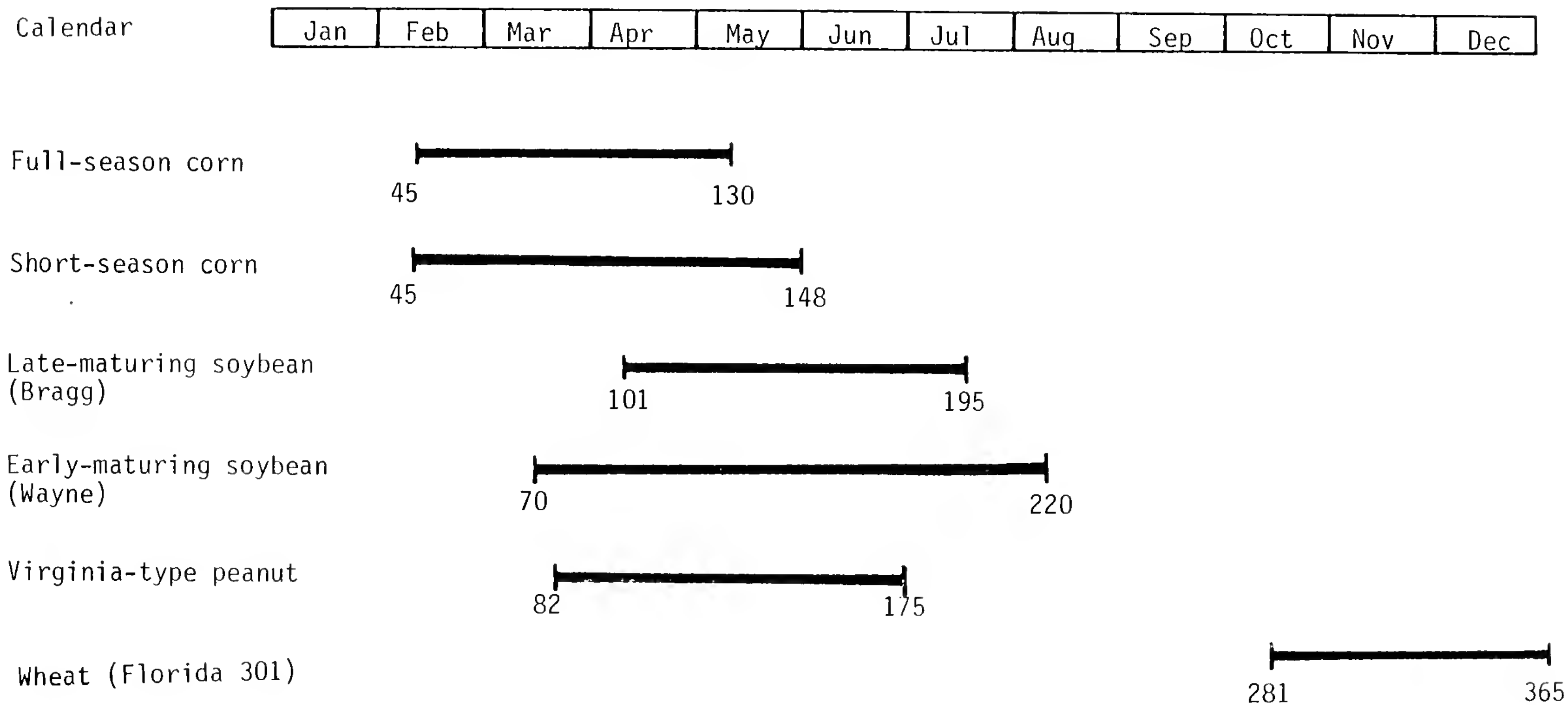


Figure 8. Time intervals during which each crop can be planted.

computing the longest path, the label-correcting method is a fundamental algorithm. This algorithm requires that the network contains no self-loops and all circuits in the network are of positive lengths. The algorithm, coded by Shier (1974) was actually used in this study.

Suppose that the K longest path lengths from source node (node 1) to all nodes i of an n-node network are required. Then a typical label-correcting algorithm proceeds according to the following three steps:

LC1. Start with an initial (lower bound) approximation to the required K longest path lengths from the source node (node 1) to each node i. That is, assign a K-vector $XV(i) = (XV_{i1}, XV_{i2}, \ldots, XV_{iK})$ to every node i, where the entries of XV(i) are listed in decreasing order.

LC2. Select a new arc and then 'process' the arc. By processing an arc (1,i) whose length is A_{1i} , this means that current K-vector for node i will be improved if possible by means of a path to node i which extends first to node 1 and which then uses the arc (1,i). More precisely, if any of the quantities $(XV_{1m} + A_{1i}: m = 1, \ldots, K)$ provides a longer path length than any one of the tentative K longest path lengths in XV(i), then the current K-vector XV(i) is updated by inclusion of this longer path length. It is to be understood that all such possible updatings of XV(i) using XV(1) are performed when processing arc (1,i).

LC3. Check the termination criterion. If satisfied stop. Otherwise, return to step LC2.

The method for processing the arcs of the network is in a fixed order: namely, in increasing order by the ending node of each arc. Thus, arcs incident to node 1 are processed before those incident to node 2, and so forth. If at some stage a node contains the approximate

lower-bound label $(-\infty,-\infty, \ldots ,-\infty)$, then no improvements can result by using such a label. It is useful to group the arcs by their ending node. Accordingly, we shall examine nodes in the fixed order 1, 2, ... ,n and shall skip the examination of a node if its label is $(-\infty,-\infty, \ldots ,-\infty)$. Here the examination of a node simply entails the processing of all arcs incident to that node. Finally, the method will terminate when after examining all nodes 1, 2, ... , n, it is found that none of the components of the current K-vectors have changed from their previous levels.

The labeling algorithm starts with the root (source node) having label zero and all other nodes having negative infinite label (INF). Then it enters a loop to update the label for each node i.

At any step of the process, the K-vector (XV(i)), associated with each node i will contain the K longest path lengths found so far from source node to the node. Moreover, these K path lengths are always distinct (apart from negative infinite values) and are always arranged in strictly decreasing order. Such an ordering allows the following two computationally important observations to be made.

(1) If the value INF is encountered in some component of a K-vector, then all subsequent components of the K-vector also contain INF values. Therefore, when updating the K-vector for node i, the K-vector for a node l incident to i need only be scanned as far as the first occurrence of an INF value since an infinite value cannot possibly yield an improved path length for node i.

(2) If (IXV), the sum of some current path length in the K-vector for node l and the arc length A_{li}, is less than or equal to the minimum element of the K-vector for node i, then no improvement in the latter K-

vector by use of the former can possibly be made. Therefore, it is appropriate to keep track of the current minimum element (MIN) of the K-vector for node i. If IXV is greater than MIN, then it is possible for an improvement to be made, as long as the value IXV does not already occur in the K-vector for node i (only distinct path lengths are retained).

As compared to the use of some general sorting routines to find the K longest elements in a list, the use of these two observations allows for a subtantial reduction in the amount of computational effort required to update the current path lengths. When all nodes have been labeled, the K longest path lengths to each node i in the network are found. From such path length information, the actual paths corresponding to any of the K longest path lengths are determined by a backward path tracing procedure.

The optimal paths joining various pairs of nodes can be reconstructed if an optimal policy table (a table indicating the node from which each permanently labeled node was labeled) is recorded. Alternatively, no policy table needs to be constructed, since it can always be determined from the final node labels by ascertaining which nodes have labels that differ by exactly the length of the connecting arc.

In essence, this latter path tracing procedure is based on the following fact. Namely, if a t-th longest path π of length l from node i to node j passes through node r, then the subpath of π extending from node i to node r is a q-th longest path for some q, $1 \leqslant q \leqslant t$. This fact can be used to determine the penultimate node r on a t-th longest path of known length l from node i to node j. Indeed, any such node r

can be found by forming the quantity $(l - l_{rj})$ for all nodes r incident to node j and determining if this quantity appears as a q-th longest path length $(q \leq t)$ for node r. If so, then there is a t-th longest path of length l whose final arc is (r,j); otherwise, no such a path exists. This idea is repeatedly used, in the manner of a backtrack procedure, to produce all paths from i to j with the length l, and ultimately all the K longest paths from node i to j.

Parameters and Variables

The hypothetical farm is located at Gainesville, Florida. The field is of an unit area (1 hectare) and of deep, well-drained sandy soil which is characterized as having a field capacity at 10% by volume and a wilting point at 5%. More specific information about the farm is discussed as follows.

Data bases contain three separate files. Weather data files in standard format contain historical, daily values of important weather variables collected from an USDA class A weather station at the Agronomy Farm, Gainesville, Florida. Available data are from the years 1954-1971 and 1978-1984. The daily weather information which is needed to run simulations consisted of Julian day of year (JULIN), maximum temperature in ^{o}C (TMAX), minimum temperature (TMIN), sunrise, hour a.m. (SNUP), sunset, hour p.m. (SNDN), total solar radiation, langleys (XLANG), wind, miles/day (WIND), and rainfall, inches/day (RAIN).

Cultivar and crop parameters are given in the text. These data are in the file named 'GROWS' and shown in Appendix D. Values for two cultivars (Bragg MG VII and Wayne MG III) of soybean were obtained from the model SOYGRO V5.0 (Wilkerson et al., 1985). Data for use in this study were the result of simulating a well-irrigated field in 1982.

Parameters for corn cultivars were based on experiments in 1980-1982 in which corn hybrid response to water stresses were studied (Bennett and Hammond, 1983; Loren, 1983; Hammond, 1981). Some of the observations included were physiological and morphological development. Data for peanut were obtained from a study by McGraw (1979). For wheat, experimental results in this study were used. Leaf area index and rooting depth of wheat, not available from the experiment were from Hodges and Kanemasu (1977).

The other file 'FACTS' shown in Appendix E provides specific information about model operation, crop production system and economical consideration. To initiate model execution, the user first provides the first decision day (IDDEC), initial soil water content (MOIST), number of crop price schemes (MXRUN) and number of crop cultivars (MXCRP) to be considered in multiple cropping system. Also required are source node (NS) and number of optimal cropping sequences (KL) searched.

Variables contained in the rest of the file are mainly relevant to system evaluation and design. Primary variables of a multiple cropping system are concerned with within-season irrigation management. These include irrigation system used (IRSYS), application rate by a strategy (RATE) and energy costs (GASPC, DSLPC, WAGE). For this study, a low-pressure center pivot system was selected. It was assumed that with a return time of one day the system was technologically capable of achieving an application rate as desired by the user. In addition to irrigation, idle periods (LIDLE) between two-crop seasons are also specified by users.

From a computerized crop budget generator (Melton, 1980), the collective costs of production for various crops were obtained.

Equations of variable irrigation costs of different systems used in the study were obtained from D'Almeda (personal communication). By regressing results which were obtained from the irrigation cost simulator (D'Almeda et al., 1982), he developed the equations for typical North Florida conditions. The other economical component of interest is crop price (PRICE), \$/kg. Current market prices (May, 1985) were provided as baseline data.

CHAPTER IV
WHEAT EXPERIMENTS

Introduction

Wheat (Triticum aestivum L.) is an important crop in the multiple cropping minimum tillage systems widely used in the Southeast USA. In this system, wheat is usually planted in the fall after soybean harvest. Despite the need for intensive management, wheat can be grown sucessfully in Florida and can make a significant contribution to Florida agriculture (Barnett and Luke, 1980).

In Florida, agriculture depends mostly upon rainfall for crop production and irrigation is needed during relatively short but numerous droughts. However, uneven rainfall distribution patterns coupled with sandy soils which have limited water storage capacities and characteristically restricted root zones thus create problems in the scheduling of irrigation. Therefore, the need for new information on timing, application intensity, method of application, and amounts of water applied exists for the region to grow wheat.

Crop growth is influenced by the process of evapotranspiration. Evapotranspiration (ET) is the combination of two processes: evaporation and transpiration. Evaporation is the direct vaporization of water from a free water surface, such as a lake or any wet or moist surface. Transpiration is the flow of water vapor from the interior of the plant to the atmosphere.

As water transpires from the leaves, the plant absorbs water from the bulk soil through its root system and transports it to the leaves to replace water transpired. Under well-watered conditions, the plants usually absorb enough water through their root systems to maintain transpiration rates at the potential rate, determined by the environment. However, as the soil around the root system dries, the ability of the soil to conduct water to the roots decreases and plants can no longer supply water fast enough to maintain the potential rate. In order to prevent leaf desiccation, the plant has a feedback control system that causes stomatal closure, thereby decreasing actual transpiration below the potential rate.

To study the problem of how to best allocate water over the crop production season, it is essential to understand and quantify the crop response to water stress throughout the irrigation seasons. Yield relationships have long been investigated. Many researchers have shown that crop dry matter production is directly related to water use by the crop throughout its growth cycle (deWit, 1958; Arkley, 1963; Hanks et al., 1969). The results demonstrate the important fact that a reduction in transpirational water use below the potential rate results in a concomitant decrease in crop biomass yield. Tanner (1981), and Tanner and Sinclair (1983) further concluded that diffusion of CO_2 into the stomata and loss of water vapor from the stomata was the coupling mechanism between biomass yield (Y) and evapotranspiration. Hence, knowledge of this ET-Y relationship is fundamental in evaluating strategies of irrigation management (Bras and Cordova, 1981; Martin et al., 1983.)

Because it is observed that interactive effects between crop growth stages existed (i.e. reduced vegetative growth during early stages caused a reduction in photosynthetic material for fruit production at the later stage), it is necessary to investigate the critical stage whose sensitivity factor to water stress is high. Peterson (1965) defined important stages of the wheat life cycle as emergence, tillering, stem extension, heading, spike development, grain setting, and grain filling and ripening. Studies of the effects of accurately defined levels of water stress on wheat growth at various stages of development were conducted by Robins and Domingo (1962), Day and Intalap (1970), Musick and Dusek (1980). Commonly, the three stages of plant development selected for irrigation were late tillering to booting, heading and flowering, and grain filling. Most of the researchers agreed that the most critical period of grain wheat for adequate soil water was from early heading through early grain filling.

The purpose of this study was to develop ET-Y functions to provide base data for improving wheat water management practices in Florida. The specific objectives of this work are: (1) to quantify the nature of ET-Y relationship for wheat crop in Northern Florida, (2) to determine the effects of timing and intensity of water deficits on wheat yield, and (3) to parameterize the crop sensitivity factors to water stress.

Experimental Procedures

Experimental Design

This study was conducted in 24 lysimeters at the Irrigation Park, University of Florida at Gainesville. The lysimeter installation was

described by Smajstrla et al. (1982). The lysimeters were cylindrical steel tanks with 2.0 meter square surface areas and 1.85 meter depth filled with an Arredondo fine sand soil taken from the site of the lysimeters. Automatically movable rainfall shelters were provided to eliminate the direct applications of rainfall on crops during the water management studies. Preplanting preparation included cultivation with a rotor-tiller and irrigation with sprinkler heads to prepare a semi-smooth surface and granulate subsurface soil.

Planting of "Florida 301" winter wheat in the lysimeters was on 29 November 1983 in 20-cm rows at a seeding rate of approximate 135 kg/ha. Seeds were manually drilled and covered lightly with soil. Fertilizer was applied at a rate of about 90-18-18 kg/ha (Nitrogen-Sulfur-Potash) in the lysimeters. One half of this amount was applied by hand at planting and the other half in late January. Unusual freezing weather on 26 December 1983 destroyed most of the seedlings in the lysimeters. Transplanting of young plants from buffer areas on 11 January 1984 made the intended study continuous. Attempts were made to maintain uniform plant densities in lysimeters, however in some cases uniformity problems did exist.

The crop growth season was partitioned as emergence to late tillering, late tillering to booting, heading and flowering, and grain filling stages. The study involved 8 treatments (4 crop stages of stress * 2 levels of stress), and each treatment was replicated three times in three lysimeters. Treatments were labeled as double-index (S,L), where S indicated stress stage and L period (weeks) of stress. In treatment (N,N), the control, the soil water at the top 50-cm depth was maintained at field capacity (11 percent volumetric water content)

throughout the growth season. There were two treatments (N,N) to ensure reliable maximum yield and potential ET during each stage. In treatment (II,*), (III,*), (IV,*), soil water contents in the top 50-cm zone were maintained at field capacity except during specific growth stages. Two levels of water stress during each growth stage were induced by omitting irrigations for 3 and 4 weeks, respectively.

A Tuesday-Friday schedule was employed to monitor soil water contents in the lysimeters during the season. Soil water contents at five depths (15, 30, 45, 75, 105 cm) of soil profile were measured with a neutron soil moisture meter (TROXLER 3220 Series.) Additional work which was performed on the same schedule included irrigation, collecting of volumes of drainage water from the lysimeters, and monitoring of crop phenology.

Irrigation decisions were made weekly immediately following neutron probe readings. Amounts of application were computed as the volume of water reduction below field capacity for the top 50-cm zone. A manually operated, pre-calibrated drip irrigation grid was designed to irrigate inside each lysimeter. A separate irrigation system was used to irrigate the buffer crop area beneath the rain-out shelters but outside of the lysimeters.

Plots were harvested on 9 May 1984. Samples of total dry matter above the ground were obtained from lysimeters by manually cutting and threshing. At the same time, plant heights were measured. Samples were then oven-dried at 95°C for 24 hours. For individual lysimeters, grain weights and related yield variables were assembled and measured for detailed analysis.

Modeling and Analysis

To account for increased sensitivity to water stress at various stages of growth, and the interactive effects between crop growth stages, a multiplicative model was selected. Jensen (1968) first developed one such model which related water stresses during various stages of crop growth to final yield. Using input of standard, available climatological data, Rasmussen and Hanks (1978) used this method sucessfully to simulate grain yields of spring wheat grown in Utah under various irrigation regimes. To estimate grain and bean production assuming that other factors, such as fertility levels, pest or disease activity, and climatic parameters are not limiting, the Jensen model is given as

$$\frac{Y}{Y_p} = \prod_{i=1}^{N} \left(\frac{ET}{ET_p}\right)_i^{\lambda_i} \tag{4.1}$$

where Y/Y_p = the relative yield of a marketable product,

ET/ET_p = the relative total ET during the given ith stage of physiological development,

λ_i = the relative sensitivity of the crop to water stress during the ith ($i = 1, 2, \ldots, N$) stage of growth.

To model this ET - Y relationship, daily ET of each lysimeter was calculated based on soil water balance method

$$ET = IR + \Delta S - DR \tag{4.2}$$

where IR = irrigation, ΔS = soil water depletion, and DR = drainage. Daily ET's were summed to calculate stage ET according to phenological

observations in the field. Data from six lysimeters, the control treatments, were used for estimation of potential grain yield and potential ET in Equation 4.1. The NLIN regression procedure (SAS, 1982) for least-squares estimates of parameters of nonlinear models (Equation 4.1) was used to calibrate crop sensitivity factors (λ_i). These values were then compared to the results of other researchers.

Results and Discussion

Field Experiment Results

The crop growth stage observations have a range of variability. In addition, the effect of water stress on crop phenology was apparent. Therefore, a stage was said to be observed when at least 50 percent of the plants that were well-irrigated were at that stage of development. Wheat phenology data observed in 1983-1984 winter season were recorded in Table 6 and shown in Figure 9, indicating a full season of 163 days. At 53 days after planting, the first node of stem was visible. Booting, when the sheath of the last leaf was completely grown out, occurred 91 days after planting. Signaled by the time first ears were just visible, heading began on March 10, which is 103 days after planting. Following the heading stage, white flowers were visible on March 22. At 141 days after planting kernels reached full size. This observation is very similar to one made at Quincy, Florida, 1977-1979, by Barnett and Luke (1980). Heading dates at Quincy were March 23 and March 27 for the 1977-1978 and 1978-1979 seasons, respectively.

Also shown in Figure 9, is the initiation of stress treatments. According to the phenological calendar, the start of water stress

Table 6. Observations of specific reproductive growth stages for winter wheat at Gainesville, FL., in 1983-1984.

Stage Description	Date	Elapsed Time after Planting
Planting	Nov. 29	1
Emergence	Dec. 4	6
Node of stem visible	Jan. 20	53
Booting	Feb. 27	91
Heading	Mar. 10	103
Flowering	Mar. 22	115
Milky-ripe	Apr. 3	127
Kernel hard	Apr. 17	141
Harvest	May 9	163

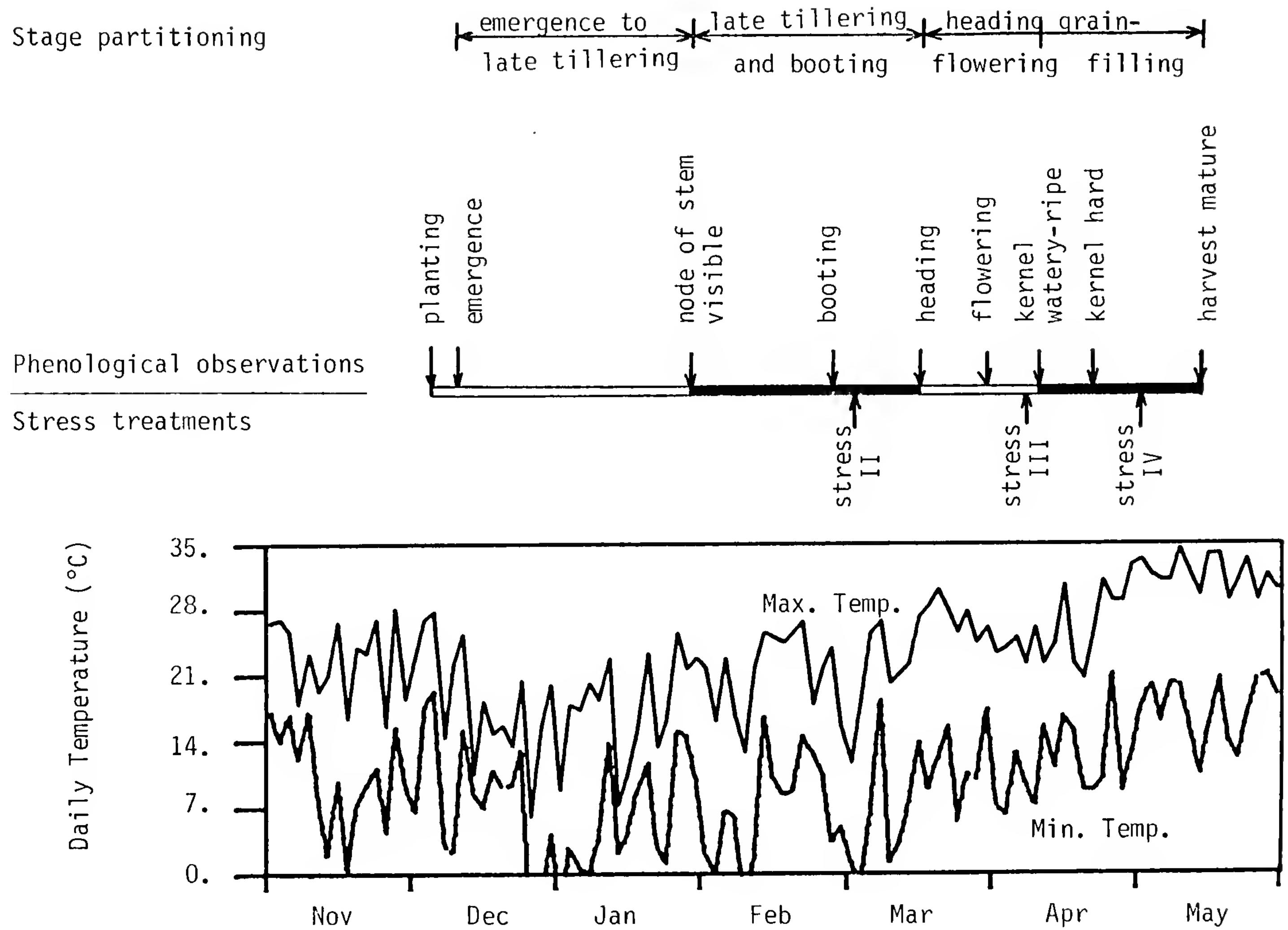


Figure 9. Phenological observations, water stress treatments, stage partitioning, and daily temperature in the winter wheat experiment, Gainesville, FL. 1983-1984.

treatments were slightly delayed. Therefore, the intended stress treatments during the grain filling stage were not completely accomplished, which resulted in duplicating treatment (IV,2) as shown in Table 7.

Detailed yield vs irrigation data are tabulated in Table 7. Effects of stress treatments on winter wheat yield are demonstrated in Table 8, and plotted in Figure 10. By observations, crop growth in lysimeters 3, 16, and 19 did not seem normal after the hard freeze. Also, difficulty had been experienced in water management in these lysimeters. Without irrigation, lysimeter 16 always had high counts of the neutron probe throughout the season. In lysimeter 3 and 19, irrigation was applied, however, it seemed that most water was drained out by suction cups at the bottom of lysimeters. Therefore, data from these three lysimeters were considered subject to an uncontrolled treatment (UC), and were excluded from the following yield analysis.

Two basically different yield levels were obtained from irrigation management. The treatments that were well-watered (N,N) and the one that experienced severe water stress during late booting stage (II,4) yielded less; whereas the rest of treatments had significantly higher yields. Comparisons of biomass yields and head numbers between treatments of heading period stress (III,*) and those stressed during grain filling stage (IV,*) show that there is no significant difference. This may be because the duration of heading to flowering stage lasts only a short period of time (Peterson, 1965; Doraiswamy and Thompson, 1982). It thus requires precise initiation of treatments to acquire differential results.

Table 7. Summary of results of winter wheat growth under various irrigation treatments, Gainesville, FL., 1983-1984.

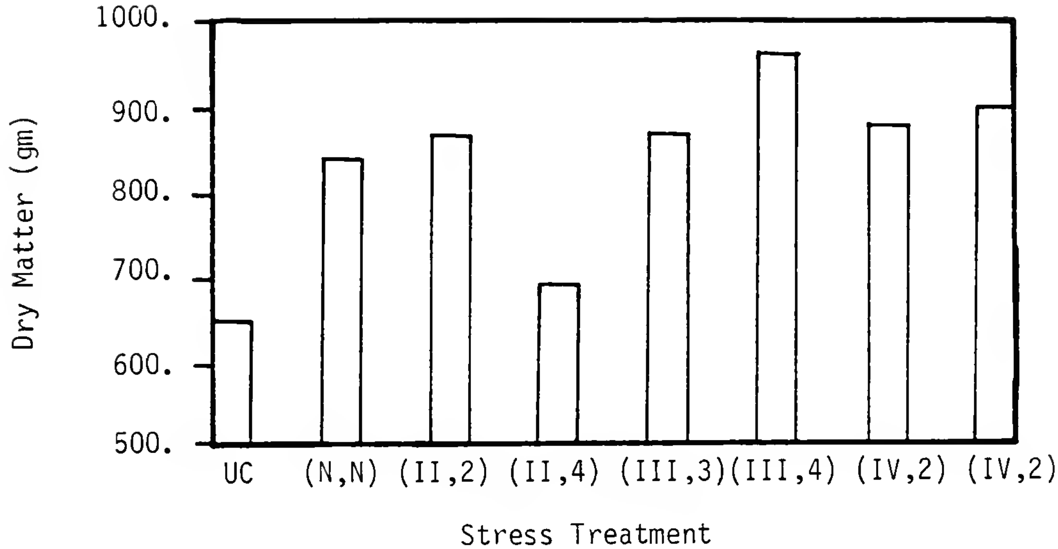
Treatment	Lysimeter	Dry Mass - gm -	Plant Ht. - cm -	No. of Heads	Head Wt. - gm -	Grain Wt. - gm -	Test Wt. -lb/bu-
(N,N)	3	620	73	577	298.3	190.1	78.5
(N,N)	16	648	78	511	325.5	224.9	81.2
(N,N)	19	670	63	576	324.9	240.6	80.4
(N,N)	7	795	68	683	395.2	305.2	81.4
(N,N)	10	840	76	574	446.6	321.4	83.1
(N,N)	21	880	73	824	459.2	358.9	81.1
(II,2)	4	742	71	663	399.9	281.6	81.2
(II,2)	12	1051	73	577	527.4	402.2	81.3
(II,2)	17	796	74	663	421.9	323.9	82.8
(II,4)	6	670	54	502	264.1	178.9	80.9
(II,4)	11	698	69	544	349.0	261.5	80.0
(II,4)	23	698	65	620	328.5	241.3	80.7
(III,3)	1	704	69	649	322.4	237.7	79.2
(III,3)	14	966	75	690	499.4	393.4	80.2
(III,3)	22	924	83	818	480.9	326.8	82.0
(III,4)	8	772	75	635	371.9	284.4	78.8
(III,4)	9	816	73	823	409.5	283.1	80.6
(III,4)	20	1291	84	710	657.0	511.5	80.4
(IV,2)	2	645	68	692	322.3	216.6	79.8
(IV,2)	13	876	72	659	467.6	369.1	84.0
(IV,2)	24	1108	86	669	559.7	419.6	80.5
(IV,2)	5	746	68	677	393.6	303.6	80.8
(IV,2)	15	811	63	504	425.8	329.6	82.1
(IV,2)	18	1128	85	776	582.5	423.9	79.5

(N,N) the control, well irrigated; (II,*) stressed during late tilling to booting; (III,*) stressed during heading and flowering; (IV,*) stressed during grain filling period.

Table 8. Treatment effects on winter wheat yield, Gainesville, FL., 1983-1984

Treatment	Dry Mass - gm -	No. of Heads	Head Wt. - gm -	Grain Wt. - gm -
UC	646.4 b	555 b	316.2 b	218.5 c
(N,N)	838.3 ab	694 ab	433.7 ab	328.5 ab
(II,2)	863.0 ab	634 ab	449.8 a	335.9 a
(II,4)	688.7 b	555 b	313.9 b	227.2 bc
(III,3)	864.7 ab	719 a	434.3 ab	319.3 abc
(III,4)	959.7 a	723 a	479.5 a	359.7 a
(IV,2)	876.3 ab	673 ab	449.9 a	335.1 a
(IV,2)	895.0 ab	652 ab	467.3 a	352.4 a
C.V. (%)	16.2	11.4	15.8	18.1

Column means followed by the same letter are not significantly different at the 5% level by Duncan's multiple range test.



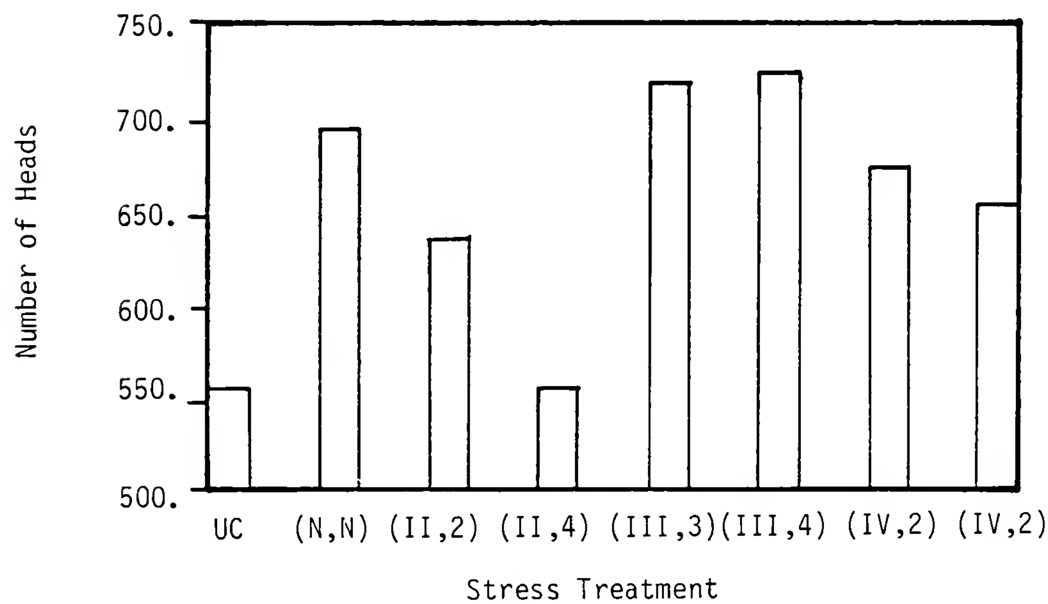
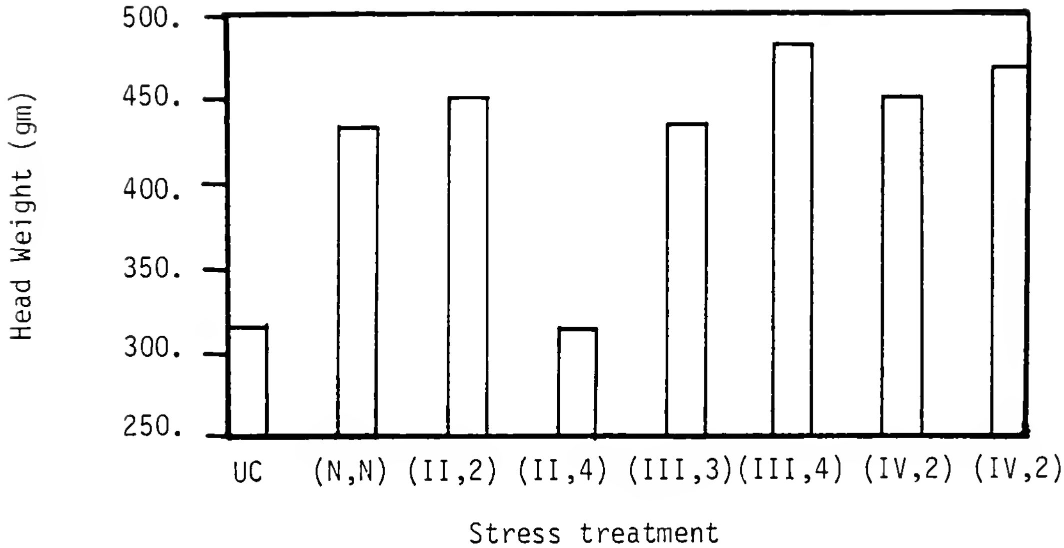


Figure 10. The effect of water stress treatment on different yield variables of wheat for each stress treatment (average of 3 replications). (a) Dry matter; (b) Number of heads; (c) Head Weight; (d) Grain weight.



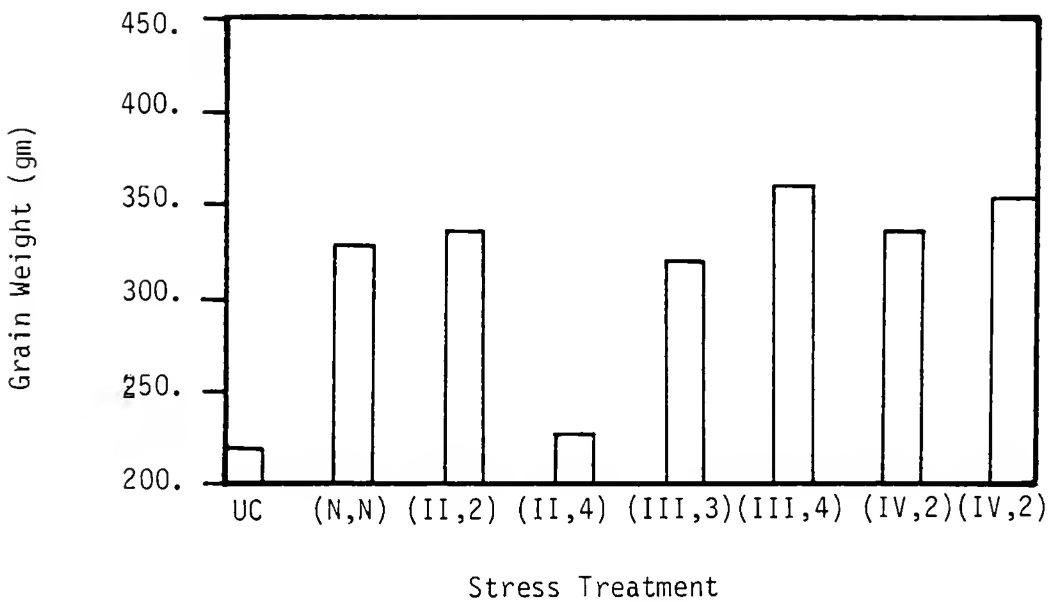


Figure 10. (continued)

Plant water stress limits leaf and tiller development during vegetative growth and stress during the late tillering to booting stage accelerates stem senescence and reduces spikelets per head (Musick and Dusek, 1980). Consequently, for treatment (II,4), the effect of extensive water stress during the late tillering stage significantly reduced grain yield by 30 percent of the well-irrigated plants. This agrees with results from Day and Intalap (1970) that water stress is more critical during late tillering than during flowering or grain filling stage.

An attempt was made to relate grain yield to seasonal irrigation and seasonal ET. A regression analysis of the effects of seasonal irrigation amounts on grain yield indicates that the linear relationship is poor with an r^2 value of 0.25. It implies that a linear model of grain yield dependent upon total irrigation or upon seasonal ET is not strongly recommended on the basis of this study. Therefore, the model of Jensen (1968) was evaluated.

Model Calibration

Phenological development occurred over a range of time and caused a large variation in the duration of various stages. The appropriate scheme of partitioning the growth season into four stages was illustrated in Figure 9. The periods of stage I, II, III, and IV were 53, 50, 24, and 36 days, respectively. Accordingly, stage ET and seasonal ET were computed and tabulated in Table 9. As explained in the last section, difficulty had been experienced in water management in lysimeters 3, 16 and 19. For these three lysimeters, the seasonal and stage-specific ET's were very low.

Table 9. Seasonal and stage-specific ET for winter wheat grown in Gainesville, FL., 1983-1984.

		Evapotranspiration (cm)					Irrigation	Grain
Treatment	Lysimeter	Stage I	Stage II	Stage III	Stage IV	Season	Applied (cm)	Yield (gm)
(N,N)	3	0.74	6.51	0.22	1.14	8.61	9.13	190.1
(N,N)	16	0.04	2.59	0.35	1.03	4.01	0.00	224.9
(N,N)	19	0.30	7.80	0.86	1.74	10.70	12.38	240.6
(N,N)	7	0.24	9.59	6.71	16.32	32.86	37.29	305.2
(N,N)	10	0.81	10.71	6.16	12.32	27.84	30.75	321.4
(N,N)	21	0.95	11.70	7.14	8.27	28.06	31.53	358.9
(II,2)	4	0.34	10.45	3.24	10.55	24.58	27.85	281.6
(II,2)	12	1.32	8.45	3.47	14.30	27.26	29.68	402.2
(II,2)	17	1.24	13.41	3.50	5.39	23.54	29.12	323.9
(II,4)	6	0.04	9.04	0.86	11.14	21.08	23.27	178.9
(II,4)	11	0.54	7.66	1.52	8.51	18.23	20.58	261.5
(II,4)	23	0.03	10.91	0.69	14.82	26.45	32.24	241.3
(III,3)	1	0.73	10.14	4.95	6.08	21.90	24.35	237.7
(III,3)	14	0.63	11.05	6.08	6.85	24.61	25.43	393.4
(III,3)	22	0.42	10.49	5.78	6.49	23.18	23.97	326.8
(III,4)	8	0.52	10.15	6.00	5.13	21.80	23.69	284.4
(III,4)	9	0.04	10.11	4.67	3.63	18.45	19.79	283.1
(III,4)	20	0.19	9.36	7.59	4.93	22.07	24.37	511.5
(IV,2)	2	0.45	8.41	5.08	3.72	17.66	20.51	216.6
(IV,2)	13	0.80	9.49	3.98	4.88	19.15	18.33	369.1
(IV,2)	24	0.88	11.77	8.84	6.62	28.11	33.05	419.6
(IV,2)	5	0.11	10.52	7.39	11.49	29.51	31.27	303.6
(IV,2)	15	0.28	8.79	2.00	2.33	13.40	14.35	329.6
(IV,2)	18	1.62	11.11	8.28	10.00	31.01	35.50	423.9

Stage I: emergence to late tillering; Stage II: late tillering to booting; Stage III: heading to flowering; Stage IV: grain filling.

Data from six lysimeters, the control units, would be used for estimation of potential grain yield and potential ET in Equation 4.1. As explained, the crop in lysimeters 3, 16, and 19 did not recover from the freeze and grow normally. Therefore, average values of data from lysimeters 7, 10, and 21 were calculated to define potential yield and potential ET values. For model calibration, calculated potential stage ET's for emergence to late tillering, late tillering to booting, heading and flowering, and grain filling 0.67, 10.67 6.67, 12.30 cm, respectively. For stage I of 53 days, potential ET of 0.67 cm was low. That is because radiation was low in December and January and irrigation was not initiated until January 13, 1984. Potential grain yield was 328 gm for a 2 meter square area.

Using data from all 24-lysimeters, calibration of λ's values (Equation 4.1) was accomplished. Values of 0.065, 0.410, 0.114, 0.026 for all λ's in Equation 4.1 gave the best fit. Predicted vs. observed yields for all data from lysimeters were given in Figure 11. Because the uncontrollable within-treatment errors and unexpected freezing weather, the $r^2 = 0.42$ does not seem high. However, the effect of critical stages of growth has been quantified.

Values of published λ's for wheat are inconsistent. The λ_i values for booting, heading, soft dought, and maturity reported by Neghassi et al. (1975) are -0.490, 2.71, -5.45, and 4.58, respectively. The negative values do not have any physical relevance. Values of 0.25 for all λ's were given by Rasmussen and Hanks (1978). By assigning the relatively short grain-filling period a λ of 0.25, Rasmussen and Hanks argued that the grain filling stage was more important in irrigated wheat production. The values obtained from this study illustrated that

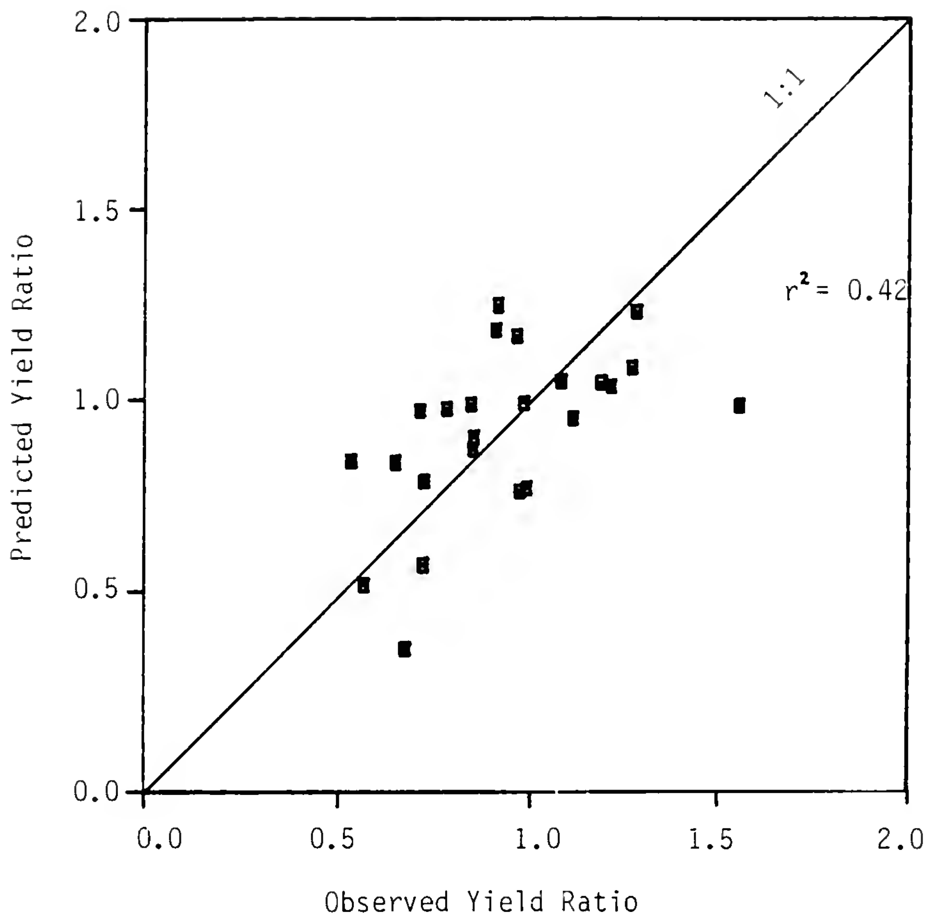


Figure 11. Plot of observed vs. predicted yield ratio for wheat.

water stress during late booting, heading and flowering stages were important. Robins and Domingo (1962), and Mogensen et al. (1985) had the same conclusion that severe water deficits should be avoided from the booting stage until the heads were filled.

In summary, the grain yield model developed in this study accounts for variables of climate and irrigation. It has been shown that the model has the capability to give very reasonable predictions of yield reductions to water stress. Coupled with a soil water balance approach, the grain yield model can be utilized effectively for water stress and irrigation management applications. It should be of particular use to economists and others concerned with the effects of drought or limited irrigation. One type of applications in using this data set will be demonstrated in the next chapter.

CHAPTER V
APPLICATION OF THE MODEL

Introduction

In Florida, where the cold season is relatively short and the water supply (precipitation and irrigation) is sufficient to grow two or more crops per year, the potential of practicing multiple cropping is high. On the other hand, irrigation development is expensive. Inasmuch as benifits from irrigation may vary appreciably from year to year, developing optimal multiple cropping systems is intended to make maximum use of the expensive irrigated land.

As the number of crops and development of new integrated management systems (i.e. tillage, irrigation, pest, fertilization, weed, etc.) increases, the problem of deciding multiple cropping sequences to be followed becomes very complex. If it is to be analyzed properly, it must be examined systematically.

An optimization - simulation model composed of submodels to integrate crops, soil - water dynamics, weather, management, and economic components has been developed to select optimal multiple cropping sequences. However, decisions about optimal multiple cropping systems are complicated by a number of factors including weather uncertainty, the complex nature of the crop's response to management strategies (i.e. irrigation), and uncertain crop prices. The application of the model refers to its use as a tool for studying various optimal cropping management decisions.

In this chapter, efforts are made to evaluate the combined simulation - optimization method for studying crop management decisions under multiple cropping; and to apply the concept to study the impact of irrigation management on the decision of crop sequencing. Specific objectives include (1) determine the efficiency and utility of the combined optimization - simulation technique as related to the multiple crop problem; (2) apply the model using north Florida as an example to study optimal multiple cropping sequences under a non-irrigated field with corn, soybean, peanut and wheat; (3) determine the effect of irrigation on optimal cropping sequences with the same crops considered; (4) evaluate the risk of various optimal cropping sequences with respect to variations in weather and crop prices; (5) suggest better cropping sequences for north Florida.

Procedures for Analyses

Crop Production Systems

Using north Florida as an example region, the model was applied to study optimal multiple cropping sequences under an irrigated or non-irrigated field. In the study, the first day of planting was set on March 16 (Julian day 75), and a 4.5-year production schedule was projected. Three crop production systems were investigated. Under system I, crops to be considered in sequential cropping were full-season corn (F.S.Corn), short-season corn (S.S.Corn), early-maturing soybean (Wayne), late-maturing soybean (Bragg), peanut, and winter wheat (Wheat 301). System II had the same crops considered, but did not allow for repeating peanut seasons in sequence. System III was studied, which

excluded peanut from cropping production. Each of these three cropping systems were studied under no-irrigation and irrigation production practices.

Constant crop prices (May 1985) through the whole 4.5-year planning period were used to project the results. Table 10 shows the crop price along with production costs and potential yields under a typical north Florida farm.

Crop Model Simulations

As described in chapter III, crop phenology, soil water balance, and crop models were developed to respond to weather and management practices for day-to-day management decisions. Therefore, weather input was an essential part of the system. Several schemes of implementation of weather data were available. They were the use of historical weather records, stochastically generated weather based on probability function, and the use of average weather data for each day. In this study, historical weather records were used to drive crop simulation models.

To study the production management decisions and crop responses in a single season, simulations on the effects of different planting dates and types of irrigation management were performed using weather records from 25 different seasons. The results were then averaged to evaluate crop response to various management strategies over the long term. In particular, the effects of management strategies on the feasibility of multiple cropping were examined.

Optimization of Multiple Cropping Sequences

Multiple cropping sequences of all three production systems for an

Table 10. Price, production cost and potential yield of different crops for a typical north Florida farm.

Crop	SI Unit			Farmer Unit		
	Potential Yield (kg/ha)	Price ($/kg)	Production Cost ($/ha)	Potential Yield (bu/ac)	Price ($/bu)	Production Cost ($/ac)
Full-Season Corn	9800	0.103	346.2	200	2.58	141.3
Short-Season Corn	8600	0.103	346.2	175	2.58	141.3
'Wayne' soybean	4010	0.238	308.2	59	6.50	125.8
'Bragg' soybean	4680	0.238	308.2	70	6.50	125.8
Peanut	3180	0.473	481.2	60	13.00	196.4
Wheat	3680	0.137	248.9	70	3.75	101.6

Source: Agronomy Facts. Fla. Coop. Ext. Serv., Insti. of Food and Agri. Sci., Univ. of Fla.

irrigated or non-irrigated field were to be explored by applying the activity network model. For the study of multiple cropping, different weather sequences were needed. There were only five 5-year-sequences weather patterns obtainable from the available 25-year weather data. Therefore, Monte Carlo simulation techniques were applied. By using a random number generator, six 1-year weather data records were randomly drawn from historical records to compose a 6-year-sequence weather file. By so doing, 20 synthetic weather patterns were generated for use. Given a weather pattern, a network of multiple cropping systems was obtained by simulations. The K longest path algorithm was then used to optimize the K optimal multiple cropping sequences of the simulated network.

Risk Analysis

Multiple cropping sequences are especially susceptible to the unpredictable influences of weather and market prices. Future uncertainties are so great that a clear answer cannot exist. Alternatively, the techniques involved in risk assessment provide assistance in quantifying these uncertainties and aid in decision-making processes.

Simulation techniques were utilized to assess the relative risk of non-irrigated multiple cropping sequences with respect to variations in weather and crop marketing. There were 10 cropping sequences used for comparison. These 10 candidates represented unique sequences chosen from those obtained from the K longest path optimization program with the best production potential.

In various optimal multiple cropping sequences, optimal planting dates of every cultivar were frequently observed. Hence, in the simulations, whenever the cultivars were scheduled after an idle period, planting would begin on observed, fixed dates. This procedure allowed an adjustable idle period which was very practical and intuitive for real production conditions.

To analyze the risk of cropping sequences under the influence of crop marketing, simulations driven by a single set of 6-year-sequence weather data were performed. While other crops price were kept constant, the increase or decrease of a crop price by 10 or 20 percent each time resulted in a total of 17 pricing schemes for use.

The results suggested by these analyses can not be extrapolated to other locations, crops, or soil types. The current version of the model is restricted to a deep, well drained, sandy soil typical of Florida conditions. However, the approach used in the analyses could be applied to other areas, soil types, and crops.

Results and Discussion

Crop Model Simulation

The growth models were used to determine crop development and yield, as well as to examine the effects of production management on final profit. Under north Florida conditions the crops were assumed to grow on the sandy soil. Tables 11 through 16 show the average results of different crops that would be considered in a multiple cropping farm.

The first aspect studied was the effect of planting date on length of growth season and final yield. For the spring/summer crop (corn,

Table 11. Simulation results[1] of irrigated and non-irrigated full-season corn grown on different planting dates for 25 Years of historical weather data for Gainesville, FL.

	Non-Irrigated			
	Planting Date			
	Feb. 15	Mar. 15	Apr. 15	May 15
Season (days)	141.2 (4.4)	124.4 (3.4)	112.3 (1.8)	105.5 (1.5)
Yield (kg/ha)	2133.0 (1759)	3556.0 (2244)	4015.0 (1624)	3771.0 (792)
Profit ($/ha)	-126.2 (180.8)	20.1 (230.6)	67.3 (166.8)	42.0 (81.4)
Act. ET (cm)	35.9 (3.5)	36.1 (2.8)	34.7 (2.2)	34.5 (2.3)
Ref. ET (cm)	49.2 (1.8)	49.5 (1.5)	48.5 (1.3)	46.2 (1.1)
Rainfall (cm)	50.8 (15.3)	48.2 (11.7)	50.9 (12.3)	59.0 (14.8)
Irrigation (cm)	0.0	0.0	0.0	0.0
	Irrigated			
Season (days)	141.2 (4.4)	124.4 (3.4)	112.3 (1.8)	105.5 (1.5)
Yield (kg/ha)	7589.0 (533)	8252.0 (156)	6363.0 (199)	4913.0 (274)
Profit ($/ha)	283.8 (56.5)	349.0 (30.2)	177.3 (27.3)	61.4 (41.0)
Act. ET (cm)	44.5 (1.7)	44.8 (1.4)	42.8 (1.2)	40.7 (1.1)
Ref. ET (cm)	49.2 (1.8)	49.5 (1.5)	48.5 (1.3)	46.2 (1.1)
Rainfall (cm)	50.8 (15.3)	48.2 (11.7)	50.9 (12.3)	59.0 (14.8)
Irrigation[2] (cm)	19.9 (4.2)	20.3 (3.9)	17.3 (2.8)	12.9 (3.8)

1. mean value followed by standard deviation in parenthesis.
2. water required to avoid most water stress.

Table 12. Simulation results[1] of irrigated and non-irrigated short-season corn grown on different planting dates for 25 Years of historical weather data for Gainesville, FL.

	Non-Irrigated			
	Planting Date			
	Feb. 15	Mar. 15	Apr. 15	May 15
Season (days)	127.2 (4.5)	110.5 (3.2)	98.5 (1.9)	91.7 (1.4)
Yield (kg/ha)	1225.0 (1105)	2685.0 (1946)	3653.0 (1675)	3733.0 (1230)
Profit ($/ha)	-219.6 (113.9)	-69.5 (200.0)	29.9 (172.1)	38.2 (126.3)
Act. ET (cm)	29.6 (3.2)	30.4 (2.7)	29.7 (1.9)	29.9 (2.2)
Ref. ET (cm)	42.7 (1.8)	42.6 (1.4)	41.9 (1.2)	39.9 (1.1)
Rainfall (cm)	43.5 (14.7)	40.3 (12.7)	41.1 (9.8)	51.7 (14.0)
Irrigation (cm)	0.0	0.0	0.0	0.0
	Irrigated			
Season (days)	127.2 (4.5)	110.5 (3.2)	98.5 (1.9)	91.7 (1.4)
Yield (kg/ha)	4540.0 (894)	7767.0 (289)	6675.0 (61)	5238.0 (78)
Profit ($/ha)	-14.8 (86.3)	295.0 (36.1)	206.4 (22.0)	92.6 (28.4)
Act. ET (cm)	36.9 (1.7)	39.5 (1.2)	38.3 (1.2)	36.1 (1.0)
Ref. ET (cm)	42.7 (1.8)	42.6 (1.4)	41.9 (1.2)	39.9 (1.1)
Rainfall (cm)	43.5 (14.7)	40.3 (12.7)	41.1 (9.8)	51.7 (14.0)
Irrigation[2] (cm)	18.0 (4.1)	20.8 (3.8)	17.7 (2.7)	13.2 (3.3)

1. mean value followed by standard deviation in parenthesis.
2. water required to avoid most water stress.

Table 13. Simulation results[1] of irrigated and non-irrigated 'Bragg' soybean grown on different planting dates for 25 years of historical weather data for Gainesville, FL.

	Non-Irrigated			
	Planting Date			
	April 10	May 10	June 10	July 10
Season (days)	186.5 (2.3)	161.4 (2.7)	137.4 (3.2)	117.5 (4.7)
Yield (kg/ha)	576.0 (215)	934.0 (365)	1622.0 (519)	1655.0 (631)
Profit ($/ha)	-170.6 (51.3)	-35.4 (86.6)	77.8 (123.3)	85.4 (149.6)
Act. ET (cm)	48.8 (4.2)	45.1 (3.9)	39.5 (3.5)	31.2 (3.0)
Ref. ET (cm)	76.0 (1.7)	65.0 (1.4)	52.4 (1.3)	40.1 (1.4)
Rainfall (cm)	84.8 (19.2)	78.8 (18.1)	68.2 (17.7)	53.7 (15.2)
Irrigation (cm)	0.0	0.0	0.0	0.0
	Irrigated			
Season (days)	186.5 (2.3)	161.4 (2.7)	137.4 (3.2)	117.5 (4.7)
Yield (kg/ha)	1294.0 (338)	1848.0 (340)	2634.0 (213)	2723.0 (304)
Profit ($/ha)	-138.1 (92.3)	247.0 (88.6)	222.3 (65.7)	251.8 (88.6)
Act. ET (cm)	58.4 (2.8)	52.5 (2.0)	44.9 (1.6)	36.0 (1.4)
Ref. ET (cm)	76.0 (1.7)	65.0 (1.4)	52.4 (1.3)	40.1 (1.4)
Rainfall (cm)	84.8 (19.2)	78.8 (18.1)	68.2 (17.7)	53.7 (15.2)
Irrigation[2] (cm)	18.2 (3.3)	14.1 (4.8)	12.6 (4.5)	11.6 (3.6)

1. mean value followed by standard deviation in parenthesis.
2. water required to avoid most water stress.

Table 14. Simulation results[1] of irrigated and non irrigated 'Wayne' soybean grown on different planting dates for 25 years of historical weather data for Gainesville, FL.

	Non-Irrigated			
	Planting Date			
	March 10	May 2	June 15	Aug. 2
Season (days)	108.2 (3.9)	87.1 (1.9)	80.5 (1.2)	85.7 (3.4)
Yield (kg/ha)	496.0 (251)	788.0 (305)	1400.0 (466)	1031.0 (475)
Profit ($/ha)	-189.6 (60.0)	-120.1 (72.4)	25.2 (110.4)	-62.6 (112.7)
Act. ET (cm)	23.2 (3.1)	25.8 (2.2)	27.1 (2.6)	21.4 (2.7)
Ref. ET (cm)	42.2 (1.6)	39.1 (1.1)	35.0 (1.0)	29.5 (1.1)
Rainfall (cm)	37.4 (13.0)	40.4 (10.3)	48.7 (13.6)	39.1 (13.8)
Irrigation (cm)	0.0	0.0	0.0	0.0
	Irrigated			
Season (days)	108.2 (3.9)	87.1 (1.9)	80.5 (1.2)	85.7 (3.4)
Yield (kg/ha)	1738.0 (212)	2484.0 (183)	2372.0 (142)	2018.0 (163)
Profit ($/ha)	30.8 (59.0)	169.5 (51.0)	177.8 (51.0)	93.3 (52.7)
Act. ET (cm)	33.0 (1.6)	33.9 (1.0)	31.5 (1.1)	26.1 (1.0)
Ref. ET (cm)	42.2 (1.6)	39.1 (1.1)	35.0 (1.0)	29.5 (1.1)
Rainfall (cm)	37.4 (13.0)	40.4 (10.3)	48.5 (13.6)	39.1 (13.8)
Irrigation[2] (cm)	18.0 (3.2)	14.9 (2.5)	10.3 (3.6)	10.3 (3.5)

1. mean value followed by standard deviation in parenthesis.
2. water required to avoid most water stress.

Table 15. Simulation results[1] of irrigated and non-irrigated peanut grown on different planting dates for 25 years of historical weather data for Gainesville, FL.

	Non-Irrigated			
	Planting Date			
	April 1	May 1	June 1	July 1
Season (days)	137.0 (2.9)	128.2 (1.4)	124.8 (1.7)	133.1 (4.0)
Yield (kg/ha)	1088.0 (346)	1328.0 (353)	1333.0 (318)	1069.0 (345)
Profit ($/ha)	33.7 (163.4)	146.6 (166.8)	149.0 (149.9)	24.4 (162.6)
Act. ET (cm)	42.2 (2.7)	41.6 (2.7)	40.2 (2.9)	36.3 (3.1)
Ref. ET (cm)	56.4 (1.5)	54.3 (1.2)	50.2 (1.3)	44.6 (1.3)
Rainfall (cm)	62.9 (13.5)	65.6 (14.5)	67.8 (18.2)	60.6 (15.4)
Irrigation (cm)	0.0	0.0	0.0	0.0
	Irrigated			
Season (days)	137.0 (2.9)	128.2 (1.4)	124.8 (1.7)	133.1 (4.6)
Yield (kg/ha)	2446.0 (78)	2393.0 (85)	1945.0 (105)	1580.0 (96)
Profit ($/ha)	516.4 (50.4)	527.0 (64.5)	337.6 (67.9)	171.6 (62.4)
Act. ET (cm)	52.1 (1.5)	49.6 (1.1)	45.8 (1.3)	41.2 (1.2)
Ref. ET (cm)	56.4 (1.5)	54.3 (1.2)	50.2 (1.3)	44.6 (1.3)
Rainfall (cm)	62.9 (13.5)	65.6 (14.5)	67.8 (18.2)	60.6 (15.4)
Irrigation[2] (cm)	21.0 (3.4)	16.2 (4.4)	13.3 (4.1)	12.4 (3.8)

1. mean value followed by standard deviation in parenthesis.
2. water required to avoid most water stress.

soybean, peanut), early spring planting lengthened the growing season. For example, there was a 36-day difference in growth seasons between early planting and late planting of corn. A difference of 69 days was even more prominent between the April and July plantings of the late-maturing 'Bragg' soybean. The effect is less significant for early-maturing 'Wayne' soybean, which has the longest season of 109 days and the shortest season of 81 days to harvest maturity.

On the average, full-season corn took 2 more weeks than short-season corn to mature. Planted on March 15, full-season corn took 125 days to grow before harvesting on June 20. So in the multiple cropping system under Florida conditions, soybean may be a good second crop to immediately follow the corn harvest. Soybean cultivars are very sensitive to photoperiod especially the late maturity groups. When 'Bragg' soybean was early planted in late spring, it required a full 6 months to grow before harvesting. If planted late, it took only 4 months to mature. On the other hand, day length had less influence on the early-maturing soybean cultivar. Hence, 'Wayne' soybean could grow 109 days before harvesting when it was planted as early as March 10. Due to these genetic traits, agronomists have advocated a soybean-soybean double cropping practice that would adopt this cultivar as the first crop. For peanuts, the range of predominate planting seasons is relatively narrow. Having an average of 130 days, the growth season of peanuts did not vary significantly.

Under unlimited soil water, yield potential of a crop is a function of photosynthetically active radiation. The length of a crop growth season generally correlates with higher yield. However, in Florida rainfall is scarce and less frequent in the spring and early summer.

Frequent, short droughts have detrimental effects on crop yields. As studied by other researchers, growth of corn, soybean or peanut is very sensitive to soil water availability during the transition period from vegetative growth to reproductive stage. Shown in Table 11, for a non-irrigated field, average yield of full-season corn planted too early (February 15) would be as much as 53 percent of that planted on its optimal date. This is also true for short-season corn, 'Bragg' soybean, 'Wayne' soybean, and peanut. The ratios are 0.33, 0.35, 0.35, 0.82, respectively. As such, factors other than solar radiation should be considered to determine optimal planting dates for various crops. Irrigation is one of the production managements which may be used to affect planting dates of crops.

The other aspect studied is the use of irrigation to improve crop production systems. As shown in Tables 11 through 14, early planting of corn and soybean using no irrigation made no profit in north Florida. The later planted crops increased profitability by increasing yield. Nonetheless, profits were not very high. To show the low profits and large variances, Figures 12 through 17 plot profit against cumulative probability. The examination of these figures shows that risk is high to grow corn and soybean early under non-irrigated conditions. For example, planting soybeans in June would result in losses 1 year out of 3 for 'Bragg', and 2 out of 5 for 'Wayne' approximately. Thus, non-irrigated corn and soybean are not relatively profitable. It is even more obvious for early-maturing 'Wayne' soybean. When 'Wayne' was planted on June 15, it was profitable, but only $25 per hectare per season. On the contrary, with or without irrigation, production of peanut is profitable under the current high market value. For peanuts

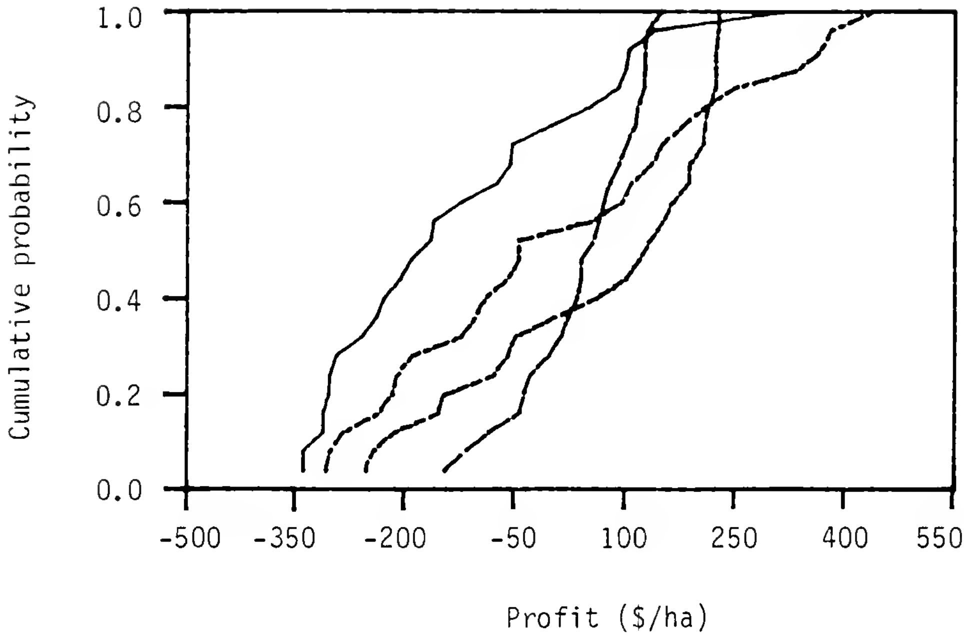


Figure 12. Cumulative probability of profit for non-irrigated full-season corn planted on Feb. 15 (——), March 15 (.—.), April 15 (---), May 15 (— —).

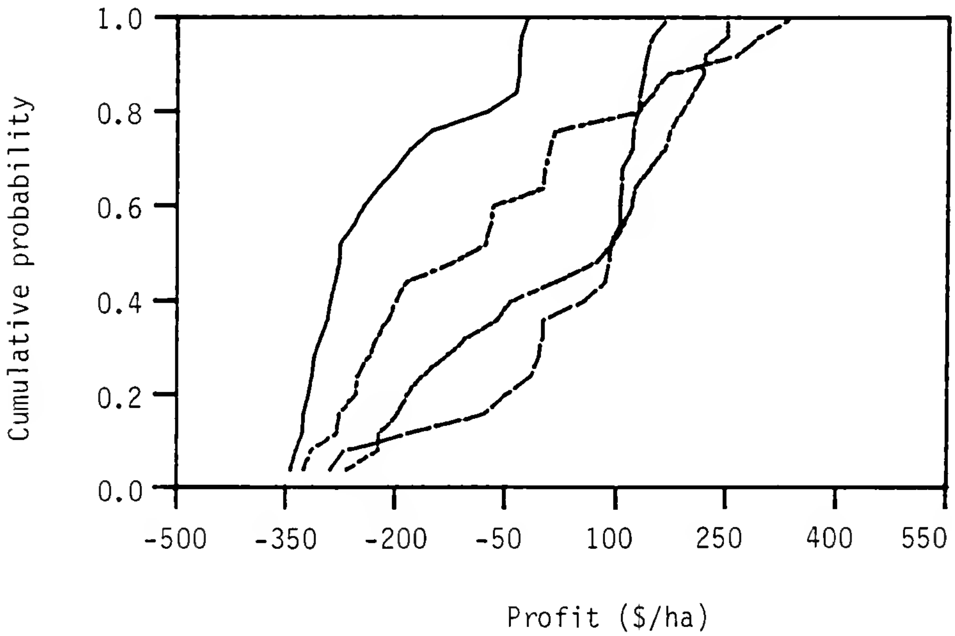


Figure 13. Cumulative probability of profit for non-irrigated short-season corn planted on Feb. 15 (——), March 15 (.—.), April 15 (---), May 15 (— —).

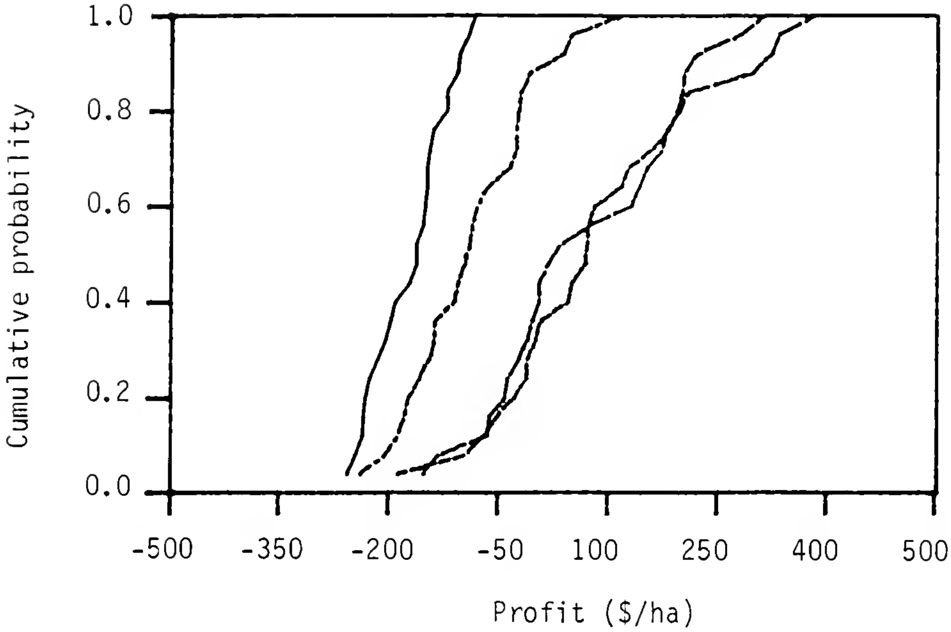


Figure 14. Cumulative probability of profit for non-irrigated 'Bragg' soybean planted on April 10 (——), May 10 (.—.), June 10 (---), July 10 (— —).

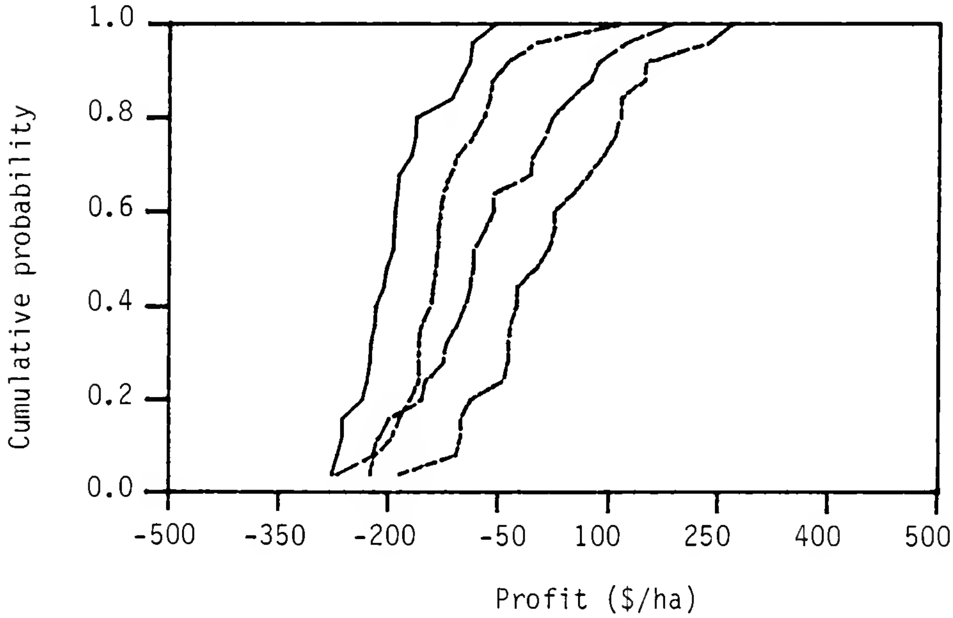


Figure 15. Cumulative probability of profit for non-irrigated 'Wayne' soybean planted on March 10 (——), May 2 (.—.), June 15 (---), August 2 (— —).

of normal-season planting (May 1), the yield of a non-irrigated field was 45 percent less than an irrigated field. Even so, a profit of $147 per hectare was attainable. Irrigation then offered more of a return at $527 per hectare.

Irrigation improves net farm income. In addition, it enhances the production system by allowing early planting of crops. Simulation results (Table 11 through 14) showed that profits were increased by irrigation when corn was planted as early as February 15, and soybeans to May 10. The results also revealed that the planting date of the highest return under an irrigated field was earlier than that of a non-irrigated field. As an example, Table 11 shows that it was better to plant non-irrigated corn on April 15 and irrigated corn on March 15 for maximum profit. Essentially, the optimal planting date occurred earlier in the season. The importance of these results was that irrigated corn and irrigated soybean made viable options for multiple cropping systems.

Wheat is drought-resistant even on the prevailing sandy soil in north Florida. As shown in Figure 17, dry land production of winter wheat usually results in positive incomes. These simulation results (Table 16) indicate, except for very late planting (on December 20), non-irrigated winter wheat production is appreciable. The use of irrigation increases yield, ranging from 7 to 20 percent above non-irrigated production. However, the increases of revenue accordingly could not compensate for the expensive irrigation cost. Therefore, under current low wheat price and high irrigation cost, irrigated production of wheat does not seem to be an economic practice in Florida.

In summary, application of irrigation to corn and soybean is essential for successful production. Irrigation makes peanut production

Table 16. Simulation results[1] of irrigated and non-irrigated wheat grown on different planting dates for 25 years of historical weather data for Gainesville, FL.

	Non-Irrigated			
	Planting Date			
	Oct. 10	Nov. 1	Nov. 25	Dec 20
Season (days)	217.3 (3.9)	192.5 (3.9)	169.0 (4.2)	147.1 (4.0)
Yield (kg/ha)	2831.0 (151)	3262.0 (193)	2856.0 (352)	2186.0 (390)
Profit ($/ha)	123.6 (18.5)	176.2 (23.6)	126.7 (42.8)	44.8 (47.5)
Act. ET (cm)	23.4 (2.1)	23.9 (2.6)	23.7 (3.3)	21.4 (3.4)
Ref. ET (cm)	41.2 (1.9)	35.4 (1.8)	32.5 (1.6)	32.5 (1.2)
Rainfall (cm)	57.4 (17.4)	52.9 (18.3)	48.4 (17.4)	43.4 (15.8)
Irrigation (cm)	0.0	0.0	0.0	0.0
	Irrigated			
Season (days)	217.3 (3.9)	192.5 (3.9)	169.0 (4.2)	147.1 (4.0)
Yield (kg/ha)	3044.0 (72)	3484.0 (43)	3188.0 (56)	2630.0 (69)
Profit ($/ha)	43.3 (27.2)	96.8 (34.7)	57.1 (32.5)	-21.2 (31.0)
Act. ET (cm)	27.6 (2.1)	28.5 (1.7)	30.3 (1.5)	29.7 (1.3)
Ref. ET (cm)	41.2 (1.9)	35.4 (1.8)	32.5 (1.6)	32.5 (1.2)
Rainfall (cm)	57.4 (17.4)	52.9 (18.3)	48.4 (17.4)	43.4 (15.8)
Irrigation[2] (cm)	15.7 (3.8)	15.7 (5.0)	16.3 (4.3)	17.9 (3.8)

1. mean value followed by standard deviation in parenthesis.
2. water required to avoid most water stress.

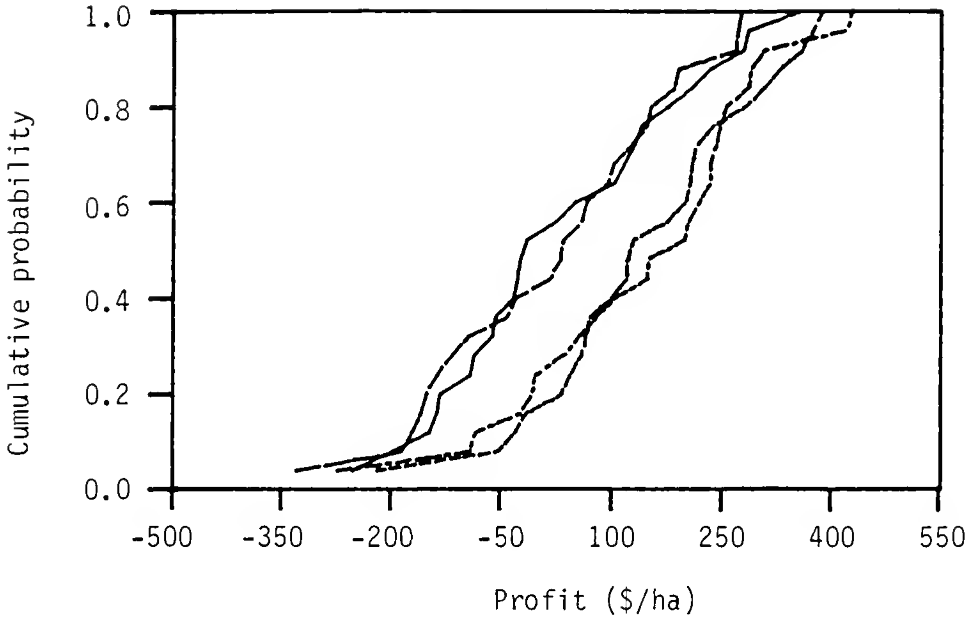


Figure 16. Cumulative probability of profit for non-irrigated peanut planted on April 1 (——), May 1 (.—.), June 1 (---), July 1 (— —).

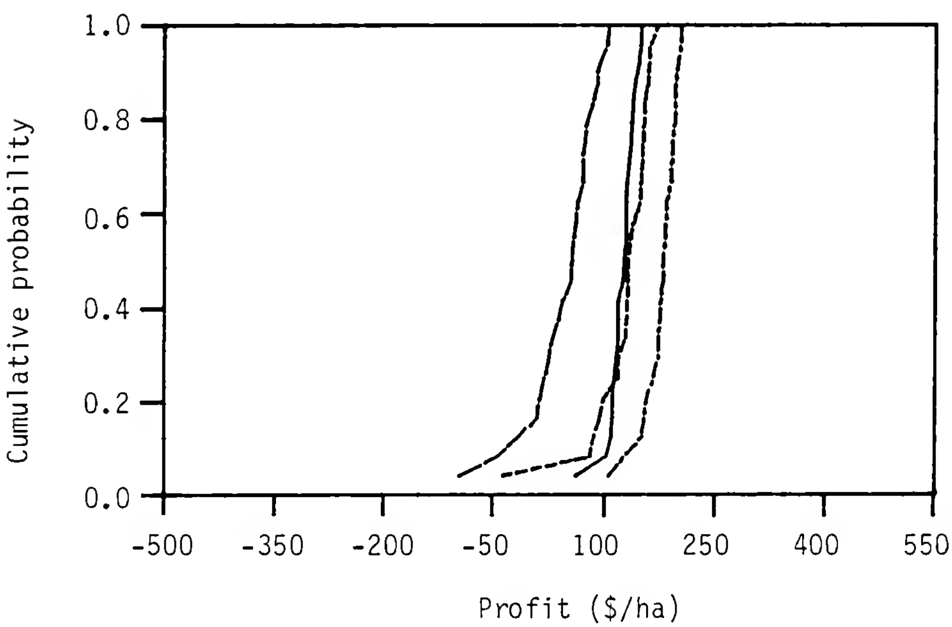


Figure 17. Cumulative probability of profit for non-irrigated wheat planted on Oct. 10 (——), Nov. 1 (.—.), Nov. 25 (---), Dec. 20 (— —).

more profitable than when it is not irrigated. Winter wheat is less sensitive to water stress. Thus, the profitability of irrigating wheat is doubtful. In addition, irrigation makes early planting of corn, soybean, and peanut profitable production systems. It therefore makes multiple cropping composed of these crops more adaptable to the north Florida region.

Evaluation of the Simulation-Optimization Techniques

To evaluate the efficiency of the simulation-optimization technique, the activity network model was applied to project optimal cropping sequences of both irrigated and non-irrigated fields for varied planning horizons. Using 20 randomly generated weather patterns to simulate activity networks, results from the model are summarized in Table 17. These data show that the networks were relatively small. Computational requirements of the model is reasonably low. For instance, it took only 21 minutes of CPU time on a mini-computer (PRIME 550) to optimize a non-irrigated multiple cropping field for a 4.5-year planning horizon. The network contained 278 nodes and 710 arcs.

The networks did not expand significantly for each additional year of planning. Accordingly, an activity network of multiple cropping systems is a good method for system representation. In addition, the longest path algorithm implemented in the model is very efficient and the time required to select the K optimal multiple cropping sequences was minor. This is suggested by two observations. First, referring to Table 17, under different irrigation options it took almost equal time to solve two networks that were different in size. Secondly, it took an additional 5 minutes of CPU time to resolve the networks that were

Table 17. Summary of network characteristics and CPU time required for various durations of planning horizon and two irrigation conditions.

	Non-Irrigated Field				Irrigated Field	
	Planning Horizon (years)					
	2.5	3.5	4.5	5.5	4.5	5.5
Nodes	147	203	278	352	325	414
Arcs	359	544	710	896	993	1283
CPU Time (min)	11	16	21	26	21	25

increased in size by 69 nodes on the average. Therefore, in the process of obtaining optimal multiple cropping sequences, the simulation of the network is more critical than optimization in terms of computational requirements. In future work, efforts should be made to design algorithms for simulation studies.

To illustrate the utility of the model, an output of the model is shown in Figure 18. A cropping sequence is a series of crops. Production of each crop is characterized by its attributes: day to plant, crop cultivar, and associated seasonal management. Also, reported in the output are soil water condition at the begining of a season (system states), length of season, and the resultant discounted net return of a crop in the sequence. The output as well lists various sequences in order of total net discounted return. In this particular run, results shown that under a non-irrigated field, peanut was a favorable summer crop and winter wheat was profitable every year. It also suggested no crop in the summer of the 4-th year. In terms of a real year, it was 1954. This year was dry. During the period from May to September, there was only 52.1 cm of rainfall compared to a 25 years average of 76.2 cm. Such a result provides the decision-makers with detailed information of the planning of cropping system under known weather conditions.

To aid in decision-making, summarized results under the influence of stochastic inputs, (i.e.: different weather patterns), are essential. Since categorizing weather input involves voluminous work, determining the effects of these factors on decisions about crop sequencing becomes exhaustive. An alternative is the statistical analysis on maximum net returns which result from various optimal cropping sequences. The

RUN # 6 WEATHER FILE:
CROP PRICE ($/KG)=0.103 0.103 0.238 0.238 0.137 0.473

SEQUENCE 1 HAVING TOTAL NET DISCOUNTED RETURN $1375

DECISION DATE	INITIAL S.W.	CULTIVAR	SEASON (DAYS)	IRRIGATION STRATEGY	DISCOUNT RETURN
MAR-16-1	10%	IDLE	42	****	0
APR-27-1	5%	IDLE	42	****	0
JUN- 8-1	8%	PEANUT	130	RAIN-FED	125
OCT-19-1	8%	WHEAT301	206	RAIN-FED	176
MAY-17-2	9%	PEANUT	129	RAIN-FED	314
SEP-27-2	7%	IDLE	42	****	0
NOV- 8-2	8%	WHEAT301	187	RAIN-FED	162
MAY-16-3	9%	IDLE	42	****	0
JUN-27-3	8%	BRAGG	132	RAIN-FED	221
NOV- 7-3	8%	WHEAT301	186	RAIN-FED	132
MAY-15-4	7%	IDLE	42	****	0
JUN-26-4	6%	IDLE	42	****	0
AUG- 7-4	7%	IDLE	91	****	0
NOV- 6-4	10%	WHEAT301	188	RAIN-FED	126
MAY-14-5	8%	PEANUT	129	RAIN-FED	119
SEP-24-5	10%	****	***	****	***

<CONTINUED>

SEQUENCE 2 HAVING TOTAL NET DISCOUNTED RETURN $1343

DECISION DATE	INITIAL S.W.	CULTIVAR	SEASON (DAYS)	IRRIGATION STRATEGY	DISCOUNT RETURN
MAR-16-1	10%	IDLE	42	****	0
APR-27-1	5%	IDLE	42	****	0
JUN- 8-1	8%	PEANUT	130	RAIN-FED	125
OCT-19-1	8%	WHEAT301	206	RAIN-FED	176
MAY-17-2	9%	PEANUT	129	RAIN-FED	314
SEP-27-2	7%	IDLE	42	****	0
NOV- 8-2	8%	WHEAT301	187	RAIN-FED	162
MAY-16-3	9%	IDLE	42	****	0
JUN-27-3	8%	BRAGG	132	RAIN-FED	221
NOV- 7-3	8%	WHEAT301	186	RAIN-FED	132
MAY-15-4	7%	IDLE	91	****	0
AUG-14-4	7%	IDLE	91	****	0
NOV-13-4	8%	WHEAT301	181	RAIN-FED	114
MAY-14-5	6%	PEANUT	129	RAIN-FED	99
SEP-24-5	10%	****	***	****	***

Figure 18. Sample output of optimal multiple cropping sequences.

SEQUENCE 3 HAVING TOTAL NET DISCOUNTED RETURN $1335

DECISION DATE	INITIAL S.W.	CULTIVAR	SEASON (DAYS)	IRRIGATION STRATEGY	DISCOUNT RETURN
MAR-16-1	10%	IDLE	42	****	0
APR-27-1	5%	IDLE	42	****	0
JUN- 8-1	8%	PEANUT	130	RAIN-FED	125
OCT-19-1	8%	WHEAT301	206	RAIN-FED	176
MAY-17-2	9%	PEANUT	129	RAIN-FED	314
SEP-27-2	7%	IDLE	42	****	0
NOV- 8-2	8%	WHEAT301	187	RAIN-FED	162
MAY-16-3	9%	IDLE	42	****	0
JUN-27-3	8%	BRAGG	132	RAIN-FED	221
NOV- 7-3	8%	WHEAT301	186	RAIN-FED	132
MAY-15-4	7%	IDLE	42	****	0
JUN-26-4	6%	IDLE	42	****	0
AUG- 7-4	7%	IDLE	42	****	0
SEP-18-4	8%	IDLE	91	****	0
DEC-18-4	10%	IDLE	91	****	0
MAR-19-5	8%	F.S.CORN	125	RAIN-FED	205
JUL-23-5	10%	****	***	****	***

<CONTINUED>

SEQUENCE 4 HAVING TOTAL NET DISCOUNTED RETURN $1334

DECISION DATE	INITIAL S.W.	CULTIVAR	SEASON (DAYS)	IRRIGATION STRATEGY	DISCOUNT RETURN
MAR-16-1	10%	IDLE	42	****	0
APR-27-1	5%	IDLE	42	****	0
JUN- 8-1	8%	PEANUT	130	RAIN-FED	125
OCT-19-1	8%	WHEAT301	206	RAIN-FED	176
MAY-17-2	9%	PEANUT	129	RAIN-FED	314
SEP-27-2	7%	IDLE	42	****	0
NOV- 8-2	8%	WHEAT301	187	RAIN-FED	162
MAY-16-3	9%	IDLE	42	****	0
JUN-27-3	8%	BRAGG	132	RAIN-FED	221
NOV- 7-3	8%	WHEAT301	186	RAIN-FED	132
MAY-15-4	7%	IDLE	42	****	0
JUN-26-4	6%	IDLE	91	****	0
SEP-25-4	10%	IDLE	91	****	0
DEC-25-4	10%	IDLE	91	****	0
MAR-26-5	10%	F.S.CORN	124	RAIN-FED	204
JUL-30-5	10%	****	***	****	***

Figure 18. (Continued).

analysis (Table 18) shows that coefficients of variation are large. In the case of a 4.5-year planning horizon, the coefficient of variation is 16.5%. It suggests that predictions of cropping sequences are sensitive to different weather inputs. In addition, coefficients of variation decrease as planning horizons increase. Hence, adoption of various cropping sequences is essential to maximize the longterm profit of cropping systems.

Based on the above discussion on evaluation and utilization of the activity network model related to decision-making on multiple cropping systems, the use of this model as a system approach to the problem is promising. In the following sections the model is applied to the study of multiple cropping systems in the region of north Florida by selecting optimal cropping sequences.

Multiple Cropping Systems of a Non-Irrigated Field in North Florida

The network model of multiple cropping systems was applied to study optimal cropping sequences under a non-irrigated field in north Florida. In order to maximize profit in the long run, a study of various cropping sequences in response to different weather patterns is necessary. Figure 19 shows the simulated optimal cropping sequences for 20 synthetic weather patterns in the region.

Under a non-irrigated farm system, winter wheat followed by peanut was such a profitable double cropping pattern that these component crops were used most frequently in every optimal 4.5-year cropping sequence. This is because in north Florida conditions both peanut and wheat do not need irrigation to make a profitable income and they do not compete for land at the same time. As studied, production of non-irrigated corn and

Table 18. Sensitivity analysis of non-irrigated multiple cropping sequences to weather patterns.

Weather Patterns	Maximum Total Net Return, ($/ha) Planning Horizon (years) 2.5	3.5	4.5	5.5
1	625	956	1053	1331
2	820	1159	1421	1628
3	966	1210	1337	1546
4	659	938	1195	1436
5	353	610	858	1156
6	998	1130	1375	1626
7	802	1028	1253	1407
8	938	1336	1583	1823
9	1121	1338	1642	1929
10	1104	1451	1555	1806
11	768	898	1247	1513
12	573	855	1112	1232
13	973	1306	1548	1671
14	1239	1373	1479	1601
15	683	1030	1287	1479
16	1105	1508	1648	1951
17	1086	1249	1507	1806
18	949	1136	1247	1492
19	637	908	1063	1305
20	652	907	1154	1543
Mean	853.6	1116.3	1328.2	1564.0
Std. Dev.	229.7	232.3	219.3	222.8
C.V. (%)	26.9	20.8	16.5	14.2
Average per year	341.4	318.9	295.2	284.4

Weather Pattern	.--year1---.---year2---.---year3---.---year4---.---year5---.
1	. BG . . FS. . WH .PE . . WH .PE .. WH .
2	. BG . . FS. . WH .FS .. WH . PE .. WH . .WN.
3	. BG . WH . PE. . WH .PE .. WH . PE .. WH . .WN.
4	. FS . . WH . . WH .PE . . WH . PE . .FS .
5	. WH . . WH .SS. . WH . PE .. WH . PE .
6	.PE . WH .PE . . WH . .BG . WH . . WH . PE.
7	.PE . WH .FS. . FS . . WH . PE. . WH . PE.
8	.PE . WH . . WH .. BG . WH . .BG . WH . PE.
9	.PE . WH . .BG . .FS . . WH . PE . . WH . PE.
10	.FS . . WH . . WH . PE. .SS .BG . WH .
11	.PE . WH . . WH . PE. . WH . . WH .PE .
12	. FS . . WH .PE . . WH . . WH . PE . .FS .
13	. PE . .FS .BG . . FS . . WH .. BG . WH .PE .
14	.SS .BG . WH . .BG . WH .PE . . WH . . WH .
15	.PE . WH .. BG . WH .PE . .SS .BG . WH . .WN.
16	.FS . . WH .PE . . WH .. BG . WH . .BG. WH . PE .
17	.PE . WH .PE . . WH .PE . . FS . . WH . .WN.
18	.PE . WH .PE .. WH .PE . . WH .PE . . WH .
19	.FS . . WH .PE . . WH .SS. . WH .PE . . WH .SS.
20	. BG . WH . . WH .PE . . WH .PE . . WH . .WN.

Figure 19. Optimal multiple cropping sequences of a non-irrigated field with full-season corn (FS), short-season corn (SS), soybean 'Bragg' (BG), soybean 'Wayne' (WN), peanut (PE) and wheat (WH), allowing continuous cropping of peanut.

soybean is risky on a seasonal basis, though, it was feasible to incorporate monocropping of soybean or corn and double cropping of wheat-corn, wheat-soybean and corn-soybean into cropping sequences as shown in Figure 19. Consequently, currently practiced, annual cropping systems in north Florida can be integrated into a longterm cropping sequence which will take into account of the variation in future weather conditions.

In contrast to real-time decision models, the model developed is for use in preseason planning. Provided that expected conditions are known, the simulation-optimization model would solve the optimal sequence to the multiple cropping system. However, future weather variations and fluctuations of crop marketing prices are not known. Hence, results of multiple simulation runs such as Figure 19 are necessary in order to make rationale decisions.

One possible use of this figure is to help answer the following question. Which crop should be planted now (March 16 for the results presented here) in order to maximize total profit over a 4.5-year period? Because future weather is unknown, this can be answered by examining the frequency of the crop as the first crop in all possible optimal cropping sequences. These optimal cropping sequences are the simulated results under to various weather patterns. As a result, a decision can be made to plant a crop according to its frequency. This process could be repeated after each crop is harvested to provide updated evaluations of crop selection.

From Figure 19, the frequency of the first selected crop was 9 for peanut, 5 for full-season corn and 4 for 'Bragg' soybean out of 20 possible choices. There was a possibility for double cropping of short-

season corn followed by 'Bragg' soybean. However, this occurred only 1 time out of 20. As a result, growing peanut was a reasonable choice to start the multiple cropping sequence. In addition, the farmer would expect to plant winter wheat after the first summer season according to these results.

From the agronomist's point of view, there may be potential problems, especially diseases and nemotodes in continuous peanut cropping. So, the optimal multiple cropping sequences suggested in Figure 19 are not without risk. Consequently, a posterior optimization technique was applied to seek alternate systems and to determine the effect of various sequences. The procedure was the same in the simulation phase of the network system. When optimizing the network, paths which have continuous peanut cropping were then discarded from optimal sequences. The modified optimal cropping sequences are presented in Figure 20. The effects of changes are then demonstrated in Table 19.

Indicated by rank, these new improved sequences did not deviate much from the first optimal (Table 19) except a few of them. These few exceptions include more than 3 peanut seasons. Peanut is the most profitable of the crops under consideration. Therefore, dropping a peanut season would mean a big loss to the farmer. However, on the average, percentage of profit reduction was small (1.9%). Without sacrificing much cumulative profit ($8 annually), the farmer could use a cropping system which emcompasses more management techniques. These modified cropping sequences are then the strategies which, in the long run, not only maximize return but also maintain the balance of natural crop environment. The posterior optimization technique proved to be a valuable tool in this application.

Weather Pattern	.--year1---.---year2---.---year3---.---year4---.---year5---.
1	. BG . .FS . . WH .SS. . WH . PE .. WH .
2	. BG . .FS . . WH .FS .. WH . PE .. WH . .WN.
3	. BG . WH . PE .. WH ..BG . WH .PE . . FS .
4	. FS . . WH . . WH .. BG . WH . PE . .FS .
5	. WH . . WH .SS. . FS . . WH . PE .
6	.BG . WH . PE. . WH .. BG . WH . . WH . PE.
7	.PE . WH .FS. . FS . . WH .PE . . FS.
8	.PE . WH . . WH .. BG . WH . .BG . WH .PE .
9	.PE . WH . .BG . .FS . . WH . .BG . WH .PE .
10	.FS . . WH . PE .. WH ..BG . .FS .BG . WH .
11	.PE . WH . . WH .. BG . WH . . WH .PE .
12	. FS . . WH . . WH . . WH . PE . .FS .
13	. PE . .FS .BG . . FS . . WH .. BG . WH .PE .
14	.SS .BG . WH . .BG . WH .PE . . WH . . WH .
15	.PE . WH .. BG . WH .PE . .SS .BG . WH . .WN.
16	.FS . . WH .PE . . WH .. BG . WH . .BG. WH . PE .
17	**
18	.PE . WH .SS. . WH . PE .. WH .WN.. WH .
19	.FS . . WH .PE . .WH .SS. . WH .PE . . WH .SS.
20	. BG . WH . . WH .PE . . WH .. BG . WH . .WN.

Figure 20. Optimal multiple cropping sequences of a non-irrigated field with full-season corn (FS), short-season corn (SS), 'Bragg' soybean (BG), 'Wayne' soybean (WN), peanut (PE), and wheat (WH), not allowing continuous cropping of peanut. (** In the post optimal analysis, search is beyond the first 100 optimal sequences.)

Table 19. Comparison of various multiple cropping systems under a non-irrigated field . System I includes corn, soybean, peanut, and wheat allowing continuous peanut croppipng. System II includes same crops as system I, but not allowing continuous peanut cropping. Systems III excludes peanut from consideration.

Weather Pattern	Max.Net Profit I	Max.Net Profit II	Max.Net Profit III	% of Profit Reduction II	% of Profit Reduction III
1	1053	1049 (2)[1]	966	0.4	8.3
2	1421	1421 (1)	1316	0.0	7.4
3	1337	1275 (24)	1110	4.6	17.0
4	1195	1159 (5)	1079	3.0	9.7
5	858	843 (3)	788	1.7	8.2
6	1375	1320 (5)	1068	4.0	21.0
7	1253	1233 (5)	1204	1.6	3.9
8	1583	1583 (1)	1428	0.0	9.8
9	1642	1618 (9)	1475	1.5	10.2
10	1555	1535 (3)	1436	1.3	7.6
11	1247	1180 (35)	998	5.4	20.0
12	1112	1091 (4)	1011	1.9	9.1
13	1548	1548 (1)	1330	0.0	14.1
14	1479	1479 (1)	1425	0.0	3.6
15	1287	1287 (1)	1191	0.0	7.4
16	1648	1648 (1)	1475	0.0	10.5
17	1507	**[2]	1242	**	17.6
18	1247	1150 (18)	1005	7.8	19.4
19	1063	1063 (1)	968	0.0	8.9
20	1154	1114 (7)	1060	3.5	8.1
Mean	1328.2	1294.5	1179.6	1.9	11.1
Std. Dev.	219.3	227.8	202.8	2.2	5.2
C.V. (%)	16.5	17.6	17.2	118	47.0

1. The rank of the optimal cropping sequence in the system I.
2. Search is beyond the first 100 optimal sequences in the post optimal analysis.

In another case, a farmer may decide to exclude peanut as an option in his cropping system because of the complexity of production, a lack of knowledge about peanut or lack of specialized equipment required for peanut. Thus, optimal cropping sequences were studied when only three crops, corn, soybean and wheat, were considered. Figure 21 shows the optimal crop sequencing for this system. The significant difference from the previous system was that wheat-soybean and wheat-corn double cropping were commomly mixed in the sequences, plus one or two seasons of monocropped corn, soybean and wheat. In this system, there were fewer crops scheduled in the sequence. Thereby, lower returns (Table 19) were obtained from the system. On the average, there was 11.1% reduction of maximum return compared to the system with peanut included.

From Figure 21, the frequency of the first selected crop was 11 for 'Bragg' soybean, 1 for 'Wayne' soybean and 6 for full-season corn out of 20 possible choices. As a result, growing 'Bragg' was a reasonable choice to start the multiple cropping system which excluded peanut for consideration. Soon after the first summer season, the following winter wheat would be planted.

Effects of Irrigation on Multiple Cropping

The multiple cropping system under a non-irrigated field has been studied. The results showed a majority of wheat-peanut double cropping as a major profitable sequence. A balance of other crops in the system was maintained though, and other practiced cropping systems, (i.e.: wheat-soybean, wheat-corn, and corn-soybean) appeared to be relatively competitive on a long-term basis. So cropping sequences under a non-irrigated field were very diversified. Under an irrigated farm,

```
weather
Pattern  .---year1--.---year2---.---year3---.---year4---.---year5---.

   1            . BG .   .FS .  . WH . SS .  . WH  . .BG . WH  .
   2            . BG .   .FS .  . WH   .FS .. WH  . .BG . WH  . .WN.
   3            . BG . WH  . .BG . WH  ..BG .  WH  .. BG . WH  .
   4        . FS . . WH  .      . WH  .. BG . WH  .        .FS .
   5                 . WH  .    . WH  .SS.    . FS .  .  WH  .WN.
   6            .BG . WH   .SS.  . WH  .. BG . WH  .       .FS .
   7             .WN. WH   .FS.    . FS .   . WH  . .BG .   .FS .
   8            . BG . WH  .      . WH  .. BG . WH  . .BG .      .BG .
   9            .BG .  WH  . .BG .   .FS .  .  WH  . .BG . WH  ..WN.
  10        .FS .  .  WH  . BG .  WH  ..BG .   .FS .BG . WH  .
  11            . BG . WH  .      . WH  .. BG . WH  .    .  WH  .SS.
  12        . FS .  . WH  .       . WH  .    . WH  .       .FS .
  13        . FS .      .FS .BG .   . FS . .  WH  .. BG .      .BG .
  14        .SS .BG . WH  . .BG . WH  .. BG . WH  .      . WH  .
  15            .BG .  WH  .. BG .   .FS .      .FS .BG . WH  . .WN.
  16        .FS .  . WH  .. BG . WH  .. BG . WH  . .BG.  WH  .
  17            . BG .  WH .. BG . WH  ..BG .  WH  .     . WH  . .WN.
  18            .BG .  WH  .SS.   . WH .SS.  . WH  . .BG . WH  .
  19        .FS.    .  WH  .SS.  .  WH .SS. .  WH  .SS.  . WH  .SS.
  20            . BG . WH  .      . WH  .. BG . WH  .. BG . WH  . .WN.
```

Figure 21. Optimal multiple cropping sequences of a non-irrigated field considering full-season corn (FS), short-season corn (SS), 'Bragg' soybean (BG), 'Wayne' soybean (WN), and wheat (WH), excluding peanut.

production of peanut became even more prominent and profitable (Figure 22). Given the current market values of the crops, corn-soybean was the only competitive cropping system which occurred with some regularity. Therefore, yearly production of peanut was the dominant sequence in multiple cropping system under irrigation.

As shown in Figure 23, when peanut was not allowed to be continuously cropped, the farmer could plant peanut one year and grow corn-soybean double cropping the other year.

Under an irrigated field in north Florida, a multiple cropping system including only corn, soybean and wheat was also studied. It was found that corn-soybean double cropping was repeated each year (Figure 24). This sequence was the most profitable cropping system under irrigation. Wheat-soybean became the substitute cropping practice in dry years. Interestingly, wheat-corn cropping sequence was not a good choice under irrigation. That was because wheat usually grows to maturity in May. The second crop, corn, could not be planted on its optimal date. Consequently, yield and profit would be reduced. Owing to this, such a practice did not compare to the more prevailing wheat-soybean system. In summary, combination of corn-soybean and wheat-soybean appeared to be the optimal cropping sequences for the farmer who uses irrigation to produce corn, soybean and wheat in north Florida.

Risk Analysis of Non-Irrigated Multiple Cropping Sequences

One of the risk assessment methods uses mean and variance values. A risk averse individual faced with two strategies of equal expected value would likely choose the one with the smaller variance. Likewise, the choice between two strategies of equal variance will be based on the

Weather Pattern	.---year1--.	---year2---.	---year3---.	---year4---.	---year5---.
1	. PE .	.PE .	.PE .	. PE .	. PE .
2	. PE .	.PE .	. WH .PE .	. PE .	.SS .BG .
3	. PE .	.PE .	. FS .BG .	. PE .	. PE .
4	. PE .	. PE .	. PE .	.PE .	.PE .
5	. PE .	. FS .BG .	. PE .	. PE .	. PE .
6	. PE .	. PE .	. FS .BG .	.PE .	. PE .
7	.SS .BG	. WH .PE .	. PE .	. PE .	. PE .
8	. PE .	. PE .	. FS .BG .	.PE .	. PE .
9	.SS .BG .	.SS .BG	. WH .PE .	. PE .	. PE .
10	. PE .	. PE .	. FS .BG .	. PE .	. PE .
11	. PE .	. PE .	. FS .BG .	. PE .	. PE .
12	. PE .	. PE .	. PE .	.PE .	.PE .
13	. PE .	.PE .	. PE .	. FS .BG .	. PE .
14	. PE .	. PE .	. PE .	. PE .	. PE .
15	. PE .	. PE .	. PE .	. FS .BG .	.SS .BG .
16	. PE .	.FS .BG .	.SS .BG .	.SS .BG .	. PE .
17	. PE .	. PE .	. FS .BG .	. PE .	.SS .BG .
18	. PE .	. PE .	. PE .	. PE .	. PE .
19	. PE .	.PE .	.PE .	.PE .	. PE .
20	. PE .	.PE .	.PE .	.PE .	. FS .WN.

Figure 22. Optimal multiple cropping sequences of an irrigated field with full-season corn (FS), short-season corn (SS), 'Bragg' soybean (BG), 'Wayne' soybean (WN), peanut (PE), and wheat (WH), allowing continous cropping of peanut.

Weather Pattern	year1	year2	year3	year4	year5
1	. PE .	.FS .WN.	. PE .	. FS .WN.	. PE .
2	**				
3	**				
4	. PE .	.FS .WN.	. PE .	. FS .WN.	. PE .
5	. PE .	.FS .BG .	. PE .	.FS .WN.	. PE .
6	. PE .	.FS .BG .	. PE .	. FS .WN.	. PE .
7	.SS .BG .	. PE .	. FS .WN.	. FS .BG .	. PE .
8	**				
9	.SS .BG .	.SS .BG . WH .PE .		.SS .BG . WH .PE .	
10	**				
11	**				
12	**				
13	. PE .	. FS .BG .	.PE .	. FS .WN.	. PE .
14	**				
15	**				
16	. PE .	.FS .BG .	.SS .BG .	.SS .BG .	. PE .
17	**				
18	**				
19	**				
20	**				

Figure 23. Optimal multiple cropping sequences of an irrigated field with full-season corn (FS), short-season corn (SS), 'Bragg' soybean (BG), 'Wayne' soybean (WN), peanut (PE), and wheat (WH), not allowing continuous cropping of peanut. (** In the post optimal analysis, search is beyond the first 100 optimal sequences.)

Weather Pattern	.---year1---.---year2---.---year3---.---year4---.---year5---.
1	.FS .WN . .FS .WN. . FS .BG . WH . .BG . .SS .WN.
2	.FS .WN . .SS .BG . WH .. BG . WH . .BG . .SS .WN.
3	.SS .BG . . FS .BG . . FS .BG . .SS .BG . WH . BG .
4	.SS .WN. . FS .WN. . FS .BG . .FS .WN. .FS .WN.
5	.SS .BG . .SS .BG . WH .. BG . .FS .WN. . FS .WN.
6	.SS .BG . .FS .WN. . FS .BG . .SS .BG . .SS .WN.
7	.SS .BG . WH .. BG . .SS .BG . .SS .BG . .SS .WN.
8	.SS .BG . WH . .BG . WH .. BG . .SS .BG . .SS .WN.
9	.SS .BG . .SS .BG . .FS .WN. . FS .WN. . FS .WN.
10	.FS .WN. WH . BG . . FS .BG . .SS .BG . .SS .WN.
11	.SS .BG . WH .. BG . .SS .BG . .FS .WN. . FS .WN.
12	. FS .WN. WH .. BG . .FS .WN. .FS .WN. .FS .WN.
13	. FS .WN. . FS .BG . .SS .WN. . FS .BG . .SS .WN.
14	. SS .BG. WH . .BG . .FS .WN. . FS .WN. . FS .WN.
15	. SS .BG. WH .. BG . WH ..BG . .FS .BG . .SS .WN.
16	.FS .WN. .FS .BG . .SS .BG . .SS .BG . .SS .WN.
17	.SS .BG . .FS .WN. . FS .BG . WH . .BG . .SS .WN.
18	.FS .WN. . FS .BG . . FS .BG . .SS .BG . WH .WN.
19	.FS .WN. .FS .BG . .SS .BG . .SS .BG . WH .WN.
20	.SS .BG . . FS .WN. . FS .BG . .FS .WN. . FS .WN.

Figure 24. Optimal multiple cropping sequences of an irrigated field considering full-season corn (FS), short-season corn (SS), 'Bragg' soybean (BG), 'Wayne' soybean (WN), and wheat (WH), excluding peanut.

higher expected value. Therefore, a mean-variance efficiency method was applied to evaluate various multiple cropping systems.

The 10 cropping sequences shown in Figure 25 were used for comparison. These 10 candidates were taken from Figure 20 to represent unique near-optimal sequences for a crop production system considering corn, soybean, peanut and wheat in a non-irrigated field. In the simulation, the fixed optimal planting date used for full-season corn was March 10; short-season corn was March 17; 'Bragg' soybean was June 8; 'Wayne' soybean was July 2; peanut was May 22; winter wheat was November 6.

Analysis of net returns of non-irrigated multiple cropping sequences in response to different weather and crop marketing are shown in Table 20 and 21, respectively. Analysis of variance indicated that the effects of changing weather and crop prices on net returns were significant at the 5% level. Thus, for the future use of the model as a real-time decision tool, inputs of weather data and crop prices deserve special attention.

Statistical analysis of the results (Table 20) showed that coefficients of variation of sequence 3, 5, 6, were higher than those of others. This demonstrated that instability of these sequences would occur from variations in weather. This is because frequent corn monocropping and/or corn-soybean double cropping occurred in these sequences. Therefore, in a long run these sequences should not be considered favorable multiple cropping practices under non-irrigated conditions.

All 10 cropping sequences were further analyzed on the basis of mean-variance efficiency criteria. A plot of mean value against

Cropping Sequence	.--year1---.---year2---.---year3---.---year4---.---year5---.
1	. BG . .FS . . WH .FS .. WH . PE .. WH . .WN.
2	. BG . WH . PE .. WH ..BG . WH .PE . . FS .
3	.PE . WH .FS. . FS . . WH .PE . . FS.
4	.PE . WH . . WH .. BG . WH . .BG . WH .PE .
5	.FS . . WH . PE .. WH ..BG . .FS .BG . WH .
6	. PE . .FS .BG . . FS . . WH .. BG . WH .PE .
7	.SS .BG . WH . .BG . WH .PE . . WH . . WH .
8	.PE . WH .. BG . WH .PE . .SS .BG . WH . .WN.
9	.FS . . WH .PE . . WH .. BG . WH . .BG. WH . PE .
10	.FS . . WH .PE . .WH .SS. . WH .PE . . WH .SS.

Figure 25. A set of optimal multiple cropping sequences for a non-irrigated field chosen from Figure 20 for additional simulation studies; FS: full-season corn, SS: short-season corn, BG: 'Bragg' soybean, WN: 'Wayne' soybean, PE: peanut, WH: wheat.

Table 20. Analysis of net returns of non-irrigated multiple cropping sequences in response to different weather patterns.

Weather Pattern	Maximum Net Return ($/ha)										
	SQ1	SQ2	SQ3	SQ4	SQ5	SQ6	SQ7	SQ8	SQ9	SQ10	Average
1	854	385	128	418	-40	350	216	389	222	342	326.4
2	1299	591	269	722	260	579	239	897	383	474	571.3
3	397	1077	514	926	623	220	658	866	747	670	669.8
4	13	699	184	435	613	-704	562	31	748	711	329.2
5	38	140	161	324	75	-389	190	83	215	362	119.9
6	488	818	125	805	410	245	614	247	879	475	510.6
7	823	1128	1107	1054	228	685	968	392	701	470	755.6
8	972	801	305	1471	836	692	548	980	1286	1032	892.3
9	652	1095	1157	1083	449	1241	912	670	863	656	877.8
10	743	804	86	594	1380	210	1028	1039	1113	1226	822.3
11	387	538	310	1128	219	674	590	538	727	355	546.6
12	69	731	160	322	600	-203	395	-127	740	554	324.1
13	862	807	693	1016	722	1354	903	691	1317	1209	957.4
14	233	671	106	515	691	-95	1531	441	838	853	578.4
15	996	541	628	615	645	456	618	1084	521	709	681.3
16	279	731	27	1182	1263	344	1050	733	1692	1140	844.1
17	588	806	133	751	527	-78	895	868	625	629	574.4
18	628	688	367	854	74	29	484	499	339	273	423.5
19	486	442	251	398	679	-164	473	156	659	892	427.2
20	610	551	-56	744	-12	-66	289	580	378	353	337.1
Statistical Significance	abc	abc	de	a	cd	e	abc	bc	ab	abc	
Mean	570.8	702.2	332.8	767.8	512.1	269.0	658.1	552.8	749.6	669.2	
Standard Deviation	345.3	241.3	332.9	321.0	382.6	513.1	341.7	352.2	380.5	301.7	
C.V. (%)	60.5	34.4	100.0	41.8	74.7	190.7	51.9	63.7	50.7	45.1	

Table 21. Analysis of net returns of non-irrigated multiple cropping sequences under different crop pricing schemes for weather pattern number 3.

Pricing Schemes	Crop Price Changed	Maximum Net Return ($/ha)									
		SQ1	SQ2	SQ3	SQ4	SQ5	SQ6	SQ7	SQ8	SQ9	SQ10
1	baseline	479	1077	514	926	623	220	658	866	747	670
2	corn(-20%)	293	1012	350	926	535	165	654	782	740	550
3	corn(-10%)	344	1045	432	926	578	192	656	824	743	609
4	corn(+10%)	449	1110	597	926	668	247	660	908	751	732
5	corn(+20%)	502	1143	680	926	713	275	662	950	755	792
6	soybean(-20%)	314	929	514	779	505	85	513	745	600	670
7	soybean(-10%)	355	1002	514	853	564	152	586	806	674	670
8	soybean(+10%)	438	1151	514	1000	683	288	732	927	821	670
9	soybean(+20%)	478	1223	514	1071	740	353	802	983	892	670
10	wheat(-20%)	208	869	378	663	421	102	394	666	481	404
11	wheat(-10%)	299	969	444	790	518	159	521	763	609	532
12	wheat(+10%)	496	1187	586	1064	728	282	797	970	886	809
13	wheat(+20%)	587	1287	652	1191	826	339	923	1068	1014	937
14	peanut(-20%)	307	859	314	753	500	47	529	625	561	457
15	peanut(-10%)	352	969	414	840	562	134	594	746	655	564
16	peanut(+10%)	442	1184	613	1012	683	306	722	984	839	775
17	peanut(+20%)	488	1295	715	1100	746	394	787	1106	934	884
Statistical Significance		h	a	g	b	f	i	e	c	d	e
Mean		401.8	1077.1	514.4	926.2	623.1	220.0	658.2	865.8	747.2	670.3
Standard Deviation		100.7	135.6	116.5	138.1	110.7	101.0	130.4	136.8	141.5	143.8
C.V. (%)		25.1	12.6	22.6	14.9	17.8	45.9	19.8	15.8	18.9	21.4

variance is helpful for the analysis. In the context of mean-variance efficiency, pairwise comparisons eliminated alternative sequences 1, 3, 5, 6, 8 from an efficient set. For the remaining efficient sequences (2, 4, 7, 9, 10), their use would depend on the farmer's preferences and local conditions. Among them, sequences 4 and 2 yielded more income with less variability. Sequence 2 and 4 continued cropping with prominent component crops of wheat-peanut and wheat-soybean, alternating each year.

The second type of variation was introduced to cropping sequences by crop marketing. In Table 20, averages of net returns of different cropping sequences were shown under various weather conditions. The average net return for weather pattern 3 was the median of all 20 weather patterns. So weather pattern 3 was chosen to represent the average climatic condition in the simulations. By simulating various pricing schemes, variability of different sequences were calculated and shown in Table 21. Of particular interest was that cropping sequences 1, 3, 6, 10 again had large coefficients of variation, while those of sequence 2, 4, 8 and were relatively small. Such results are very similar to those on the basis of risk to weather variability. Therefore, statistically speaking, sequences 4 and 2 were preferred to sequence 3 and 6.

In summary, for a higher net return with a smaller variation under non-irrigated conditions, farmers could adopt either sequence 4 or 2, which include mostly peanut, wheat, and 'Bragg' soybean in summer-winter cropping each year.

Applications to Other Types of Management

Farming is much more than irrigation management. To farm profitably for any significant period of time, it is also necessary to understand the maintenance or improvement of organic matter, soil structure and fertility, as well as the control of insects, weeds, diseases, and erosion. Because of these many areas of management the problem of deciding multiple cropping sequences to be followed become more complex, and it must be examined systematically if it is to be analyzed properly. The framework developed in the study is readily applicable to these other areas of cropping management.

Application of the model to the specific area of pest and disease management will be considered as an example of implementation procedure. In multiple cropping systems, pests are of concern throughout the entire cropping period. In order to minimize pest damage to multiple cropping systems, a model of pest and disease balance is needed for pest management just as a soil water balance model was produced earlier for irrigation management. By representing the state of the system by pest population, such as nematodes, and using a pest model to simulate the state, a network model thus can be constructed for studying optimal cropping sequences with particular application to pest control and management.

To study more refined multiple cropping sequences, both irrigation and pest management could be integrated. In such a case, levels of soil water content and pest population would then be used to represent the state of the system. There is no evidence that pest problems would affect water conditions in the soil. Accordingly, soil water balance model may not need to be modified. However, incidences of pests depend

on weather and the condition of soil. Therefore, more sophisticated pest population models that are capable of responding to irrigation strategy and pest management are required.

With these models at hand, the methodology developed is ready to study the effects of irrigation and pest management on multiple cropping system. Furthermore, provided other areas of management have been investigated, more detailed, complicated multiple cropping systems can be explored.

CHAPTER VI
SUMMARY AND CONCLUSIONS

Summary and Conclusions

Multiple cropping is one of the means to increase and help stabilize net farm income where climatic and agronomic conditions allow its use, such as in Florida. With several crops to be examined simultaneously, the design of multiple cropping sequences becomes complex. Therefore, a systems approach is needed. This study has successfully developed a framework for optimizing the multiple cropping system by selecting cropping sequences and their management practices.

By combining simulation and optimization techniques, the deterministic activity network model for the multiple cropping system was the best choice from those that were investigated in terms of system representation and computational requirements. With particular application to irrigation management, models of crop yield response, crop phenology, and soil water balance were required for system simulation. The level of sophistication of models has been determined and component models were developed and implemented. Afterward, the longest path algorithm was utilized to seek the K optimal multiple cropping sequences for the production system considered.

By applying the methodology to study a farm in north Florida, optimal multiple cropping sequences were identified. Under a non-irrigated farm, winter wheat followed by either soybean, corn or peanut

forms the annual profitable cropping component in a multiple cropping sequence. Especially favorable is the cropping of wheat-peanut. Another significant conclusion to be drawn concerned the effect of irrigation management on optimal multiple cropping sequences. After the investment in an irrigation system, the multiple cropping system coupled with irrigation was shown to almost double a farm net income in 4.5 years. An irrigated peanut crop was found to be prominent and was scheduled each year assumming that the high value of peanut will continue. In a system in which peanut was not considered an option, inclusion of irrigated wheat-corn cropping could not be recommended as a profitable multiple cropping system. Instead, double cropping of corn-soybean was the main scheme under irrigation with the possible substitution of wheat-soybean.

Suggestions for Further Research

The conclusions made with regard to multiple cropping systems in north Florida were under the assumption that farming management other than irrigation were optimally practiced. So the importance of irrigation management on implementation of multiple cropping systems can be stressed. In the meantime, a great effort has been devoted to developing the methodology. The methodology developed is capable of incorporating other aspects of farming into an integrated approach for studying multiple cropping. However, basic research to quantify the effect of farm management on crops and the development of component models to describe each management area would be a noteworthy contribution to the complete system by using this methodology.

Eventually, the model could be used in an expert system by the farmer to help configure their cropping enterprise. The implementation of input data of weather and crop price has been found to have great influence on decision-making. The exploration of decisions based on the logistic of inputing these parameters may be a fruitful exercise in future research efforts.

APPENDIX A
GENERAL DESCRIPTIONS OF SUBROUTINES

Main Program

The main program, as an executive, takes control of the process for optimizing multiple cropping systems. It calls various subroutines to accomplish every procedure, system description, generation of network, and network optimization. General descriptions of these subroutines are given in Table 22. The flow diagram has been previously presented in the section of model implementation.

Simulation proceeds node by node to create a network. At a node, new nodes are generated (NNEW ≠ 0) and subroutine ORDER is called to expand a network. Simulation then advances to the next node (NEXT=NEXT+1). Toward the end of a planning horizon, the crop growth season is too long to be in time for harvest (TOSHT=1), and the simulation is terminated. When the network generation is completed, the main program moves on to optimize the network created and then to output results.

Subroutine DATIN

Subroutine DATIN is first called from the main program to depict a multicropping production system by inputing user-defined variables and parameters of a system. This information may be categorized by historical weather, crop growth, and production facts. These data for DATIN are stored in input data files, 'WFILE', 'GROWS', and 'FACTS',

Table 22. General descriptions of subroutines used in optimizing multiple cropping systems.

Subroutine	General Descriptions
	System Description
DATIN	called to input information concerning production system.
	Generation of Network
FIELD	A simulation model in turn calls phenology, soil water balance, crop response submodels for generating nodes and arcs.
PHENO	crop phenology model.
SWBAL	soil water balance model.
PROFT	calculates net discounted profit by assessing crop yield.
WCALC	calculates hourly temperature from daily maximum and minimum temperatures.
PENMAN	Penman formula for estimating potential evapotranspiration.
RADCL	equations for calculating daily insolation.
SORT	used to order newly created nodes by increasing order of time argument.
ORDER	organizes the expanding network by numbering nodes in increasing order by time argument.
	Network Optimization
LISTN	called to list arcs in increasing order by arc ending node.
KPATH	K longest paths algorithm.
TRACE	produces all paths having any of the K longest path lengths.
DCODE	decode and summarize cropping sequences.

respectively. Free format is used to read in data. As soon as values are available, parameters derived from these input values are calculated. Subroutine DATIN therefore solely completes the phase of system description in the whole process of optimization.

Subroutine FIELD

In order to have a multiple cropping system network, simulation techniques are applied to generate new nodes and new arcs. Subroutine FIELD therefore is used as a planning manager to monitor field activities and to organize simulation proceedings. Procedures to simulate crop growth and state transition (soil water contents) have been detailed in model implementation section of chapter III.

Subroutine FIELD is composed of two independent sections. The first section is for considering main crop production. The second section primarily simulates bare soil evaporation during cropping idle time. After simulating the soil water status under various cropping systems, results are stored in temporary arrays for future network expansion. The number of new nodes generated in a simulation cycle, NNEW, is used as one of criteria for terminating network generation phase. Namely, when NNEW $\neq$ 0, simulations are continued.

Subroutine ORDER(NEXT,NNEW)

In the process of optimizing a network, it is advantageous to have a network whose nodes are sequentially numbered from a source node to a terminal node. The network will be sequentially ordered according to its first coordinate of a node. Subroutine ORDER exactly accomplishes the objective.

Each node (NODES) is identified by two coordinates. The first coordinate is decision date (IP(NODES)). The second one is soil water content (IW(NODES)). An arc is specified by its starting node (FROM(ARC)) and ending node (TO(ARC)). Data related to a specific arc are crop choice, length of growing season, management strategy, and net return, and are stored in the arrays JC, JG, JS, and JR, respectively.

A total of NNEW nodes are to be added to expand a network by extending arcs from node NEXT to each new node. In terms of decision date, when the first node of the new list of nodes is later than the last node of the existing network, direct appending is only required and expansion is complete. Otherwise, it is necessary to insert new nodes and re-number an old network.

Insertion of a new node in the existing network is made by examining the latest node first. As an insertion is located, a further test on whether the node has been numbered will be done. If the node is an existing one, new arcs are added to a network, and bookkeeping is executed. Otherwise, re-numbering of nodes and subsequent update of arc data need be completed, before a correct insertion can be made possible. Accordingly, subroutine ORDER would output a sequentially numbered network.

Subroutine SORT(NNEW)

For easily numbering nodes, new nodes need to be ordered before being appended to the existent network. When there are a total of NNEW nodes generated by simulations at a presently considered decision node, subroutine SORT is used to order new nodes by increasing order of the next decision date (IH(I)). INDEX is an array whose I-th element gives

the number of simulation runs that results in the node (X(I),Y(I)). It is then used in subroutine ORDER as an index to search out relevent data of an arc connecting the current decision node to newly appended nodes.

Subroutine LISTN

The K longest paths algorithm requires that a network representation is such that an arc list is a non-decreasing sequence of arc ending nodes. To serve the purpose, subroutine LISTN prepares a description of a given network to be read in from subroutine KPATH. The network description is achieved by specifying for each arc of a network a record containing its starting node, its ending node and its length. In this application, an arc length is the net profit associated with a cropping decision. The essential operation in LISTN is sorting the records in increasing order by arc ending node (TO(ARC)).

Subroutine KPATH

Subroutine KPATH implements an optimization algorithm to seek all K longest, distinct path lengths of a network. It uses the label-correcting method as discussed in the text. First of all, a description of the given network is read in. The records are assumed to be stored in increasing order by arc ending node. Moreover, the nodes are assumed to be numbered consecutively from 1 to NODES. As the network is entered, the variables and arrays needed by labeling procedure and TRACE subroutine are created. The labeling algorithm starts with the root (source node) having label zero and all other nodes having infinite label (INF). Then it enters a loop to update the label for each node 1.

Subroutine TRACE

Subroutine TRACE will produce all paths (JJ) from source node (NS) to terminal node (NF), having any of the K longest path lengths (LL). The algorithm to reconstruct optimal paths from the final node labels has been presented in chapter III.

Subroutine WCALC

This subroutine calculates hourly temperatures and a temperature factor for use in phenological stage prediction. Provided with daily maximum (TMAX(N)) and minimum (TMIN(N)) temperatures as well as time of sunrise (SNUP(N)) and sundown (SNDN(N)), WCALC is able to calculate hourly temperatures (THR(IXX)).

It assumes that hourly temperatures between 2-hour after daylight and sundown are sinusoid-like. After sundown temperature cools off and presumably decreases linearly to its minimum just at 2-hour after sunrise of the next day. Accordingly, the first part of WCALC is coded.

The remainder of subroutine WCALC enables computation of temperature factors on development (PHTFCT(IXX)) for use in phenological calculations. Its calculation is based on a hypothetical curve which is well defined by three variables, the optimal (TOPT), minimum (TPHMIN) and maximum temperature (TPHMAX). The hypothesis is: Rate of development, which is the inverse of the duration of a phase, is linearly related to temperature if temperature is below an optimal value. The relationship was given in Figure 2, where the development rate is normalized to the rate at the optimum temperature for development. Above the optimum temperature, development rate decreases linearly to zero. The variables TPHMIN, TOPT, and TPHMAX are read into

the model in subroutine DATIN. In DATIN, the high and low temperature slopes (PHCON3, PHCON5) of the relationship and intercepts (PHCON4, PHCON6) are also calculated for use in this subroutine.

Subroutine PHENO

This subroutine is called each day to compute the phase of the crop development from one phenological stage to the next. All crop development phases depend on temperature. In PHENO, this temperature effect is expressed as physiological time (PHTFCT(IXX)) which is calculated hourly in subroutine WCALC. By cumulating the factors, the rate of development (DTX) during any particular day as a function of temperature is assessed. Subroutine PHENO is divided into sections. Each section independently supports phenological modeling of a specific crop.

Subroutine SWBAL

With the discussed procedures in the soil water balance model, subroutine SWBAL estimates actual evaporation and transpiration as affected by rainfall and irrigataion use. Simultaneously, soil water status is updated properly. For each stage, actual ET and potential ET are accumulated.

Subroutine PENMAN

The Penman formula is coded in this subroutine for calculation of potential evapotranspiration at a given leaf area index.

Subroutine PROFT

Provided with stage ET's and season depth of irrigation water, this subroutime returns a net discounted income from production of a specific crop.

APPENDIX B
SOURCE CODE OF SUBROUTINES

```
C   **   OPTIMAL & SYSTEM ANALYSIS OF MULTICROPPING SYSTEMS
C   **   Y.J.TSAI VERSION2.1  05/15/85 AG.EN. U. OF FLORIDA
C
C      MAIN PROGRAM
C
      INTEGER ARC,FROM,TO,MKMND,SW1,IND(6)
      LOGICAL TOSHT
$INSERT NAMCM1
$INSERT NAMCM2
C
      CALL DELETE ('SERIES',6,IC)
C
      IO(1)=4
      IO(2)=5
      IO(3)=6
      IO(4)=7
      IO(5)=8
      IO(6)=9
      IIN2=14
      IIN3=15
      IOU1=16
      IOU2=17
      IOU3=18
      IOU4=19
C
      IIWEA=0
   50 IIWEA=IIWEA+1
C
C *** DATA INPUT PHASE
C
      DO 80 I=1,6
        IND(I)=MOD(INT(RND(0)*100),25)+1
   80 CONTINUE
      CALL DATIN(IND)
C
      IIRUN=0
  100 IIRUN=IIRUN+1
      CALL DELETE ('NETWOK',6,IC)
      CALL DELETE ('CROPIN',6,IC)
C
C        INITIALIATION PHASE
C
        DO 200 M=1,2100
```

```
          DO 150 N=10,5,-1
            NODE(M,N)=0
  150     CONTINUE
  200   CONTINUE
        ARC=0
        NODES=1
        NEXT=0
        IP(1)=IDDEC
        IW(1)=MOIST
        NODE(IP(1),IW(1))=1
        NNMAX=IDDEC+1640
C
C *** PERFORM SIMULATIONS TO CREATE NEW NODES & ARCS
C
  300   NEXT=NEXT+1
        TOSHT=.FALSE.
        MKMND=IP(NEXT)
        SW1=IW(NEXT)
        NNEW=0
C
        CALL FIELD(TOSHT,NNEW)
C
        IF (NNEW .NE. 0) THEN
C
C       ARRANGE NEW NODES IN INCREASING ORDER OF DECISION DATES
C
          CALL SORT(NNEW)
C
C *** EXPAND NETWORK, NUMBER NODES IN INCREAING ORDER OF DECISION DATES
C
          CALL ORDER(NEXT,NNEW)
          GOTO 300
        ELSE
          IF (.NOT. TOSHT) THEN
            GOTO 300
          END IF
        END IF
C
C       NO MORE SIMULATION NEED, CONNECT DUMMY ARCS TO SINK NODE (NF)
C
        NOMORE=NEXT
        NF=NODES+1
        DO 400 I=NOMORE,NODES
          ARC=ARC+1
          FROM(ARC)=I
          TO(ARC)=NF
          JC(I,NF)=0
          JG(I,NF)=0
          JS(I,NF)=0
          JR(I,NF)=0
  400   CONTINUE
        NODES=NODES+1
C
C       FORMAT ARC LIST IN INCREASING ORDER BY ARC ENDING NODE NUMBER
```

```
C
        CALL LISTN
C
C *** APPLY LONGEST PATH OPTIMIZATION ALGORITHM
C
        CALL KPATH
C
C *** PRINT OUT SUMMARY RESULTS
C
        CALL DCODE
C
        IF (IIRUN .LT. MXRUN) THEN
          GOTO 100
        END IF
        IF (IIWEA .LT. MXYER) THEN
          GOTO 50
        END IF
C
      STOP
      END
C     ****************************************************************
C
      SUBROUTINE DATIN(IND)
C
C     ****************************************************************
$INSERT NAMCM1
$INSERT NAMCM2
      DIMENSION ZZ(5),THRVAR(3),VRFRC(3),WEATR(25),IND(10)
      DATA WEATR/'G54W','G55W','G56W','G57W','G58W','G59W','G60W',
     $           'G61W','G62W','G63W','G64W','G65W','G66W','G67W',
     $           'G68W','G69W','G70W','G71W','G78W','G79W','G80W',
     $           'G81W','G82W','G83W','G84W'/
C
C
      DO 100 J=1,6
        WFILE(1)=WEATR(IND(J))
C
        CALL OPENF(IO(J),WFILE(1),4,40,0,1,2,3,IC)
C
C *** WEATHER DATA, VARIABLE FILENAMES
C
        DO 90 K=1,365
        I=365*(J-1)+K
        READ(IO(J),5) JULN(I),TMAX(I),TMIN(I),SNUP(I),SNDN(I),XLANG(I),
     $                WIND(I),RAIN(I)
   05   FORMAT(3X,I3,2(1X,F6.2),2(1X,F7.2),9X,F5.1,11X,F4.0,1X,F4.2)
        SNDN(I)=12.+SNDN(I)
        RAIN(I)=2.54*RAIN(I)
        WIND(I)=1.61*WIND(I)
   90   CONTINUE
C
        CALL CLOSE(IO(J),IC)
  100 CONTINUE
C
```

```
      IF (IIWEA .LE. 1) THEN
C
        CALL OPENF(IIN2,'FACTS',5,40,0,1,2,3,IC)
        CALL OPENF(IIN3,'GROWS',5,40,0,1,2,3,IC)
C
C *** DATA CONCERNED WITH PROFIT ESTIMATE, FILE 'FACTS'
C
        READ (IIN2,*) NS,KL,MXRUN,MXYER
        READ (IIN2,*) IDDEC,MOIST,MXCRP
        READ (IIN2,*) (LIDLE(J),J=1,3)
        READ (IIN2,*) IRSYS,(RATE(J),J=1,3)
        READ (IIN2,*) (PDCST(J),J=1,MXCRP)
        READ (IIN2,*) GASPC,DSLPC,WAGE,DEPRE
C       DO 150 I=1,MXRUN
          READ (IIN2,*) (STD(1,J),J=1,MXCRP)
C 150   CONTINUE
        DO 200 I=1,MXRUN
          READ (IIN2,*) (PRICE(I,J),J=1,MXCRP)
  200   CONTINUE
C
C       IRRIGATION COST PER APPLICATION (IN-ACRE) FOR VARIOUS SYSTEMS
C
        DO 240 N=1,4
          UIRCS(N,1)=0.0
  240   CONTINUE
        DO 250 I=2,3
        UIRCS(1,I)=6.96-(.25*RATE(I))+(.04*RATE(I)*RATE(I))+3.5*(DSLPC
     $             -1.2)+(.0275+.065/RATE(I))*(WAGE-4.0)
        UIRCS(2,I)=5.08-(.265*RATE(I))+(.045*RATE(I)*RATE(I))+2.1*(DSLPC
     $             -1.2)+(.0275+.065/RATE(I))*(WAGE-4.0)
        UIRCS(3,I)=8.91-(1.01*RATE(I))+(.17*RATE(I)*RATE(I))+4.2*(DSLPC
     $             -1.2)+(.055+.25/RATE(I))*(WAGE-4.0)
        UIRCS(4,I)=8.94-(.24*RATE(I))+(.04*RATE(I)*RATE(I))+5.3*(DSLPC
     $             -1.2)+(.055+.0625/RATE(I))*(WAGE-4.0)
  250   CONTINUE
C
C *** DATA FOR PHENOLOGY AND MULTIPLICATIVE YIELD MODELS, FILE 'GROWS'
C
C       HEAT DEGREE DAYS FOR CORN AND PEANUT
C
        READ (IIN3,*) (HDGE(1,J),J=1,4)
        READ (IIN3,*) (HDGE(2,J),J=1,4)
        READ (IIN3,*) (HDGE(6,J),J=1,4)
C
C       COEFFICIENTS FOR WHEAT PHENOLOGY
C
        READ (IIN3,*) (A0(J),J=1,5)
        READ (IIN3,*) (A1(J),J=1,5)
        READ (IIN3,*) (A2(J),J=1,5)
        READ (IIN3,*) (B0(J),J=1,5)
        READ (IIN3,*) (B1(J),J=1,5)
        READ (IIN3,*) (B2(J),J=1,5)
        READ (IIN3,*) (B3(J),J=1,5)
        READ (IIN3,*) (B4(J),J=1,5)
```

```
C
C      VALUES FOR SOYBEAN PHENOLOGY AND THEIR CALCULATION
C
       READ (IIN3,*) TOPT,TPHMIN,TPHMAX
       PHCON3=1.0/(TOPT-TPHMIN)
       PHCON4=-PHCON3*TPHMIN
       PHCON5=1.0/(TOPT-TPHMAX)
       PHCON6=-PHCON5*TPHMAX
C
       READ (IIN3,*) (ZZ(J),J=1,5)
       DO 330 I=1,2
         DO 320 J=1,5
           PHTHRS(I,J)=ZZ(J)
  320    CONTINUE
  330  CONTINUE
C
       DO 350 I=1,2
         READ (IIN3,*) Y1,Y2,Y3,Y4
         TNLG1(I)=Y1
         TNLG0(I)=Y2
         THVAR(I)=Y3
         DHVAR(I)=Y4
         PHCON2(I)=(THVAR(I)-DHVAR(I))/(TNLG1(I)-TNLG0(I))
         PHCON1(I)=DHVAR(I)-PHCON2(I)*TNLG0(I)
C
         READ (IIN3,*) (THRVAR(J),J=1,3)
         READ (IIN3,*) (VRFRC(J),J=1,3)
         PHTHRS(I,7)=THRVAR(1)
         PHTHRS(I,10)=THRVAR(2)
         PHTHRS(I,11)=THRVAR(3)
         PHTHRS(I,6)=VRFRC(1)*PHTHRS(I,10)
         PHTHRS(I,8)=VRFRC(2)*PHTHRS(I,10)
         PHTHRS(I,9)=VRFRC(3)*PHTHRS(I,10)
  350  CONTINUE
C
C      CROP POTENTIAL YIELD AS A FUNCTION OF PLANTING DATES
C
       READ (IIN3,*) (XXSOW(1,J),J=1,8)
       READ (IIN3,*) (YYILD(1,J),J=1,8)
       READ (IIN3,*) (XXSOW(2,J),J=1,8)
       READ (IIN3,*) (YYILD(2,J),J=1,8)
       READ (IIN3,*) (XXSOW(3,J),J=1,8)
       READ (IIN3,*) (YYILD(3,J),J=1,8)
       READ (IIN3,*) (XXSOW(4,J),J=1,8)
       READ (IIN3,*) (YYILD(4,J),J=1,8)
       READ (IIN3,*) (XXSOW(5,J),J=1,8)
       READ (IIN3,*) (YYILD(5,J),J=1,8)
       READ (IIN3,*) (XXSOW(6,J),J=1,8)
       READ (IIN3,*) (YYILD(6,J),J=1,8)
C
C      CROP LAI DATA
C
       READ (IIN3,*) (XXLAI(1,J),J=1,11)
       READ (IIN3,*) (YYLAI(1,J),J=1,11)
```

```
        READ (IIN3,*) (XXLAI(2,J),J=1,11)
        READ (IIN3,*) (YYLAI(2,J),J=1,11)
        READ (IIN3,*) (XXLAI(3,J),J=1,11)
        READ (IIN3,*) (YYLAI(3,J),J=1,11)
        READ (IIN3,*) (XXLAI(4,J),J=1,11)
        READ (IIN3,*) (YYLAI(4,J),J=1,11)
        READ (IIN3,*) (XXLAI(5,J),J=1,11)
        READ (IIN3,*) (YYLAI(5,J),J=1,11)
        READ (IIN3,*) (XXLAI(6,J),J=1,11)
        READ (IIN3,*) (YYLAI(6,J),J=1,11)
C
C       ROOT GROWTH DATA
C
        READ (IIN3,*) (XXROT(1,J),J=1,11)
        READ (IIN3,*) (YYROT(1,J),J=1,11)
        DO 380 J=1,11
          XXROT(2,J)=XXROT(1,J)
          YYROT(2,J)=YYROT(1,J)
  380   CONTINUE
        READ (IIN3,*) (XXROT(3,J),J=1,11)
        READ (IIN3,*) (YYROT(3,J),J=1,11)
        DO 400 J=1,11
          XXROT(4,J)=XXROT(3,J)
          YYROT(4,J)=YYROT(3,J)
  400   CONTINUE
        READ (IIN3,*) (XXROT(5,J),J=1,11)
        READ (IIN3,*) (YYROT(5,J),J=1,11)
        READ (IIN3,*) (XXROT(6,J),J=1,11)
        READ (IIN3,*) (YYROT(6,J),J=1,11)
C
C       CROP SENSITIVITY FACTORS
C
        DO 500 I=1,MXCRP
          READ (IIN3,*) (CS(I,J),J=1,4)
  500   CONTINUE
C
        CALL CLOSE(IIN2,IC)
        CALL CLOSE(IIN3,IC)
C
      END IF
      RETURN
      END
C     *****************************************************************
C
      SUBROUTINE FIELD(TOSHT,NNEW)
C
C     *****************************************************************
$INSERT NAMCM1
$INSERT NAMCM2
      INTEGER CLEND,MKMND,SW1,SW2,TODAY,SEASN
      LOGICAL FIRST,MATUR,TOSHT
C
      CLEND=MOD(MKMND,365)
C
```

```
C *** CONSIDER CROP(S) ONLY FOR THE CURRENT SEASON
C
      DO 500 KCROP=1,MXCRP
        IF (KCROP .EQ. 1) THEN
          IF (CLEND.LT.45 .OR. CLEND.GT.130) THEN
            GOTO 500
          END IF
        ELSE
          IF (KCROP .EQ. 2) THEN
            IF (CLEND.LT.45 .OR. CLEND.GT.148) THEN
              GOTO 500
            END IF
          ELSE
            IF (KCROP .EQ. 3) THEN
              IF (CLEND.LT.101 .OR. CLEND.GT.195) THEN
                GOTO 500
              END IF
            ELSE
              IF (KCROP .EQ. 4) THEN
                IF (CLEND.LT.70 .OR. CLEND.GT.220) THEN
                  GOTO 500
                END IF
              ELSE
                IF (KCROP .EQ. 5) THEN
                  IF (CLEND.LT.281 .OR. CLEND.GT.355) THEN
                    GOTO 500
                  END IF
                ELSE
                  IF (CLEND.LT.91 .OR. CLEND.GT.175) THEN
                    GOTO 500
                  END IF
                END IF
              END IF
            END IF
          END IF
        END IF
C
C       LPP=MOD(INT(RND(0)*100),3)+1
C       IHP=MOD(INT(RND(0)*100),3)+1
        LPP=2
        IHP=3
C
C *** WITHIN-SEASON IRRIGATION STRATEGIES CONSIDERED
C
C       DO 400 IRSGY=1,2
        IRSGY=1
C       IF (KCROP .NE. 5) THEN
C         IRSGY=2
C       ELSE
C         IRSGY=1
C       END IF
C
          TODAY=MKMND
          NNDAY=0
```

```
      ISTG=1
      MATUR=.FALSE.
      FIRST=.TRUE.
C
C     LAND PREPARATION PERIOD
C
      DO 50 IL=1,LPP
        TODAY=MKMND+NNDAY
        NNDAY=NNDAY+1
        CALL ETBARE
   50 CONTINUE
C
      FIRST=.TRUE.
      SW2=ISCRE(THETA)
C
C     CROP GROWTH PERIOD
C
  100 CALL PHENO(KCROP)
      TODAY=MKMND+NNDAY
      NNDAY=NNDAY+1
      CALL SWBAL(KCROP,IRSGY)
      IF (TODAY.GE.NNMAX .AND. ISTG.LT.4) THEN
        TOSHT=.TRUE.
        GOTO 500
      END IF
C
      IF (.NOT. MATUR) THEN
        GOTO 100
      END IF
C
C     HARVESTING PERIOD
C
      DO 150 IV=1,IHP
        TODAY=MKMND+NNDAY
        NNDAY=NNDAY+1
        CALL SWBAL(KCROP,IRSGY)
  150 CONTINUE
C
      SEASN=NNDAY
C
C     MAKE A PRODUCTION SEASON AS UNITS OF A WEEK
C
  200 IF (MOD(NNDAY,7) .NE. 0) THEN
        TODAY=MKMND+NNDAY
        NNDAY=NNDAY+1
        CALL SWBAL(KCROP,IRSGY)
        GOTO 200
      END IF
C
      CALL PROFT(KCROP,IRSGY,MONEY)
C
C     DISCARD AN ARC OF NEGATIVE RETURN
C
      IF (MONEY .GE. 0) THEN
```

```
C
C           DISCRETE SOIL WATER CONTENT
C
            SW2=ISCRE(THETA)
C
C           WETHER AN ARC IS REPLACED WITH LARGER RETURN ?
C
            TODA1=TODAY+1
            IF (NNEW .GT. 0) THEN
              DO 250 I=1,NNEW
                IF (TODA1.EQ.IH(I) .AND. SW2.EQ.ISW(I)) THEN
                  NN=I
                  IF (MONEY .LE. IR(NN)) THEN
                    GOTO 400
                  ELSE
                    GOTO 300
                  END IF
                END IF
  250         CONTINUE
            END IF
C
C           STORAGE TEMPORARY INFORMATION OF ARCS & NODES
C
            NNEW=NNEW+1
            NN=NNEW
C
  300       IH(NN)=TODA1
            ISW(NN)=SW2
            IC(NN)=KCROP
            IG(NN)=SEASN
            IS(NN)=IRSGY
            IR(NN)=MONEY
            NEW(IH(NN),ISW(NN))=NN
          END IF
C
  400   CONTINUE
  500 CONTINUE
C
      IF (.NOT. TOSHT) THEN
C
C *** CONSIDER IDLE PRACTICE AS OPTIONS OF CROPING SEQUENCE
C
      DO 700 IDLE=1,2
        TODAY=MKMND
        NNDAY=0
        FIRST=.TRUE.
        IDUR=LIDLE(IDLE)
        IF ((MKMND+IDUR) .LE. NNMAX) THEN
C
C *** SIMULATE ET OF BARE SOIL
C
  550     IF (NNDAY .LT. IDUR) THEN
            TODAY=MKMND+NNDAY
            NNDAY=NNDAY+1
```

```
            CALL ETBARE
            GOTO 550
          END IF
C
          SW2=ISCRE(THETA)
C
          MONEY=0
C
          TODA1=TODAY+1
          IF (NNEW .GT. 0) THEN
            DO 600 I=1,NNEW
              IF (TODA1.EQ.IH(I) .AND. SW2.EQ.ISW(I)) THEN
                NN=I
                IF (MONEY .LE. IR(NN)) THEN
                  GOTO 700
                ELSE
                  GOTO 650
                END IF
              END IF
  600       CONTINUE
          END IF
C
          NNEW=NNEW+1
          NN=NNEW
C
  650     IH(NN)=TODA1
          ISW(NN)=SW2
          IC(NN)=MXCRP+1
          IG(NN)=LIDLE(IDLE)
          IS(NN)=4
          IR(NN)=MONEY
          NEW(IH(NN),ISW(NN))=NN
        END IF
  700 CONTINUE
      END IF
C
      RETURN
      END
C     ******************************************************************
C
      SUBROUTINE PHENO(CROP)
C
      ******************************************************************
C *** THIS SUBROUTINE IS CALLED EACH DAY TO COMPUTE THE PHASE OF THE
C *** CROP FROM ONE PHENOLOGICAL PHASE TO THE NEXT.
C
      DIMENSION PHTFCT(24),PHTFCY(24)
      INTEGER CROP,TODAY
      LOGICAL FIRST,MATUR
$INSERT NAMCM1
C
C *** CALCULATE PHYSIOLOGICAL DAYS ACCUMULATED TODAY (DTX)
C
      N=TODAY
```

```
      DTX=0.
      CALL WCALC(PHTFCT,PHTFCY)
      DO 10 IXX=1,24
        DTX=DTX+PHTFCT(IXX)/24.
   10 CONTINUE
C
      GOTO (100,100,300,300,200,100), CROP
C
C     ---------------------------------------------------------------
C *** FOR CORN, PEANUT PHENOLOGY IS A HEATING DEGREE DAY FUNCTION
C     ---------------------------------------------------------------
C
  100 CONTINUE
      IF (FIRST) CUMDT=0.
      CUMDT=CUMDT+DTX
      IF (CUMDT .GE. HDGE(CROP,ISTG)) GOTO 150
      RETURN
C
  150 ISTG=ISTG+1
      IF (ISTG .GT. 4) MATUR=.TRUE.
      RETURN
C
C     ---------------------------------------------------------------
C *** FOR WHEAT, A MULTIPLICATIVE MODEL (ROBERTSON, 1968)
C     ---------------------------------------------------------------
C
  200 CONTINUE
      IF (FIRST) JJ=1
      IF (ISTG .GT. 1) GOTO 220
      IF (JJ .NE. 1) GOTO 220
      V1=1.
      GOTO 230
  220 JJ=ISTG+1
      DLEN=SNDN(N)-SNUP(N)
      X=DLEN-A0(JJ)
      V1=A1(JJ)*X+A2(JJ)*X*X
C
  230 TEMPMX=TMAX(N)*1.8+32.
      TEMPMN=TMIN(N)*1.8+32.
      Y=TEMPMX-B0(JJ)
      V2=B1(JJ)*Y+B2(JJ)*Y*Y
C
      Z=TEMPMN-B0(JJ)
      V3=B3(JJ)*Z+B4(JJ)*Z*Z
C
      DELX=V1*(V2+V3)
      IF (DELX .LE. 0.) DELX=0.
      XM=XM+DELX
      IF (XM .GE. 1.) GOTO 250
      RETURN
C
  250 IF (JJ .NE. 1) GOTO 260
      JJ=2
      XM=0.0
```

```
      RETURN
C
  260 ISTG=ISTG+1
      XM=0.
      IF (ISTG .GT. 4) MATUR=.TRUE.
      RETURN
C
C     ------------------------------------------------------------------
C *** FOR SOYBEAN, A MODEL OF PHYSIOLOGICAL DAY AND NIGHT ACCUMULATOR
C     ------------------------------------------------------------------
C
  300 CONTINUE
      IF (CROP .EQ. 3) JJ=1
      IF (CROP .EQ. 4) JJ=2
      IF (FIRST) NPHEN=1
C
  310 GO TO (320,320,320,350,320,350,350,350,350,350,320),NPHEN
C
  320 CONTINUE
      PHZDAY = PHZDAY + DTX
      IF (PHZDAY .LT. PHTHRS(JJ,NPHEN)) GO TO 460
      IF (NPHEN .NE. 1) PHZDAY = 0.0
      GO TO 440
C
  350 CONTINUE
      XNT = 0.0
      TNTFAC = 0.0
C
C     COMPUTE CHANGE IN NIGHTTIME ACCUMULATOR DURING THE PREVIOUS
C     NIGHT (USING TEMPERATURES AFTER SUNSET YESTERDAY AND BEFORE
C     SUNRISE TODAY IN THE CALCULATIONS)
C
      DO 360 IXX = 12,24
        XTMP = IXX
        IF (XTMP .LT. SNDN(N-1)) GO TO 360
        XNT = XNT + 1.0
        TNTFAC = TNTFAC + PHTFCY(IXX)
  360 CONTINUE
      DO 370 IXX = 1,12
        XTMP = IXX
        IF (XTMP .GT. SNUP(N)) GO TO 380
        XNT = XNT + 1.0
        TNTFAC = TNTFAC + PHTFCT(IXX)
  370 CONTINUE
C
  380 CONTINUE
      TNTFAC = TNTFAC / XNT
      DURNIT = 24. - SNDN(N-1) + SNUP(N)
      IF (DURNIT .LE. TNLG1(JJ)) DNIT = THVAR(JJ)
      IF (DURNIT .GE. TNLG0(JJ)) DNIT = DHVAR(JJ)
      IF (DURNIT.LT.TNLG0(JJ) .AND. DURNIT.GT.TNLG1(JJ))
     +     DNIT = PHCON1(JJ) + PHCON2(JJ) * DURNIT
      TDUMX = TNTFAC * (1.0 / DNIT)
      ACCNIT = ACCNIT + TDUMX
```

```
C
      IF (ACCNIT .LT. PHTHRS(JJ,NPHEN)) GO TO 460
      IF (NPHEN .LT. 6) ACCNIT = 0.0
C
  440 CONTINUE
      NPHEN = NPHEN + 1
      IF (NPHEN .EQ. 5) ISTG=2
      IF (NPHEN .EQ. 8) ISTG=3
      IF (NPHEN .EQ. 10) ISTG=4
      IF (NPHEN .GT. 11) MATUR=.TRUE.
C
C     IF GOING FROM NIGHT TIME ACCUMULATOR TO PHYSIOLOGICAL DAY
C     ACCUMULATOR, START ACCUMULATING IMMEDIATELY RATHER THAN
C     WAITING UNTIL THE NEXT DAY
C
      IF (NPHEN .EQ. 5 .OR. NPHEN .EQ. 11) GO TO 310
  460 CONTINUE
      RETURN
      END
C     ****************************************************************
C
      SUBROUTINE SWBAL(CROP,IRSG)
C
C     ****************************************************************
      INTEGER CROP,TODAY,SW2
      LOGICAL FIRST,MATUR
      DIMENSION DEPLE(3),SWTHRS(7,4),XXR(11),YYR(11),XXL(11),YYL(11)
$INSERT NAMCM1
      DATA DEV/10./,ALFA/0.234/
      DATA THETWP/4.4894E-02/,THETFC/10.00E-02/
      DATA EPS/0.00001/,RNMAX/250./,DEPLE/.00,.60,.40/
      DATA SWTHRS/.20,.20,.20,.20,.20,.15,.15,
     $            .50,.50,.55,.55,.65,.60,.40,
     $            .70,.70,.75,.75,.80,.80,.70,
     $            .45,.45,.50,.50,.50,.50,.30/
C
      IF (ISTG .GT. 4) ISTG=4
      IF (FIRST) THEN
C
C *** INITIALIZE PARAMETERS FOR CURRENT SEASON
C
        DO 20 I=1,11
          XXR(I)=XXROT(CROP,I)
          YYR(I)=YYROT(CROP,I)
          XXL(I)=XXLAI(CROP,I)
          YYL(I)=YYLAI(CROP,I)
   20   CONTINUE
        DO 30 I=1,4
          ETPO(I)=0.0
          ETAC(I)=0.0
   30   CONTINUE
        DDRY = 0
        ORISW=FLOAT(SW2)/100.
        APPLY=2.54*RATE(IRSG)
```

```
        RANFL=0.0
        DPIRR=0.
        RZDEP=0.0
        RZDP=0.0
        WCMAX=THETFC-THETWP
        WCAVL=ORISW-THETWP
        WEP = DEV * WCMAX
        WE =  DEV * WCAVL
        WTP = 0.00001
        WT = 0.00001
        RATIO=WE/WEP
      END IF
      FIRST=.FALSE.
C
      N=TODAY
      RANFL=RANFL+RAIN(N)
      IF (.NOT. MATUR) THEN
C
C     IMPLEMENT IRRIGATION STRATEGY
C
        IF (RATIO.LT.DEPLE(IRSG) .AND. RAIN(N).LT.0.2) THEN
          FXIN=RAIN(N)+APPLY
          DPIRR=DPIRR+APPLY
        ELSE
          FXIN=RAIN(N)
          DPIRR=DPIRR
        END IF
C
C     NO IRRIGATION NEED WHILE HARVESTING
C
      ELSE
        FXIN=RAIN(N)
      END IF
C
C *** CALCULATE ROOT DEPTH AND UPDATE AVAILABLE SOIL WATER
C
      RZDP=RZDEP
      RN=FLOAT(NNDAY)
      RZDEP=TABEX(YYR,XXR,RN,11)
      IF (RZDEP .GT. DEV) THEN
        RZINC = RZDEP-RZDP
        WT = WT + WCAVL * RZINC
        WTP = WTP + WCMAX * RZINC
      END IF
      WTZ = WEP+WTP
C
C *** CALCULATE POTENTIAL ET (PET) & POTENTIAL SOIL EVAPO. (EP)
C
      XLAI = TABEX(YYL,XXL,RN,11)
      CALL PENMAN(XLAI,PET,EP)
C
C *** CALCULATE POTENTIAL TRANSPIRATION RATE (RITCHIE, 1972)
C
      IF (XLAI .LT. 0.1) TP=0.00001
```

```
      IF (XLAI.GE.0.1 .AND. XLAI.LE.3.0) TP=PET*(0.7*SQRT(XLAI)-0.21)
      IF (XLAI .GT. 3.0) TP=PET
C
C     THE FOLLOWING ADDED FOR SOIL FLUX TERM
C
      IF (WT/WTP .LT. 0.2) WT = WT+0.05
C
C     CALCULATE TRANSPIRATION RATE, T
C
      WET1 = WE + WT
      THETA = THETWP+WET1/RZDEP
      RATIO = WET1 / WTZ
      THETAC = THETWP+SWTHRS(CROP,ISTG)*WCMAX
      IF (THETA .GE. THETAC) THEN
        T = TP
      ELSE
        T = TP * (THETA-THETWP)/(THETAC-THETWP)
      END IF
C
C     CALCULATE EVAPORATION RATE ,  E
C
      EP = AMIN1(AMAX1(0.00001,(PET-T)),EP)
C
C     COUNT NUMBER OF DAYS WITHOUT RAIN OR IRRIGATION
C     TWO-STAGE EVAPORATION PROCESS IMPLEMENTED
C
      IF (FXIN .GE. EPS) THEN
        DDRY = 0
        E = EP
      ELSE
        DDRY = DDRY + 1
        E = ALFA*(SQRT(DDRY)-SQRT(DDRY-1))
        IF (E .GT. EP) THEN
          E = EP
        END IF
      END IF
C
C *** UPDATE SOIL WATER STATUS
C
C     RAINFALL
C
      IF (FXIN .GE. EPS) THEN
        WE = WE + FXIN
        IF (WE  .GE.  WEP)  THEN
          WT = WT + WE - WEP
          WE = WEP
        END IF
      END IF
C
C     EVAPORATION ZONE
C
      IF (E .GT. WE) E = WE
      WE = WE - E
C
```

```
C     TRANSPIRATION ZONE
C
      WET = WE + WT
      IF (WET .LT. EPS) THEN
C
C     DO NOT LET SOIL WATER CONTENTS DECREASE BELOW PWP
C     (IF SOIL WATER DROPS BELOW ZERO, DRAW ON TRANSIENT WATER,
C     AND RESET THE WATER CONTENTS TO ZERO.)
C
C       EXCESS = EXCESS + WE + WT
        WE = 0.00
        WT = 0.00
      ELSE
        WE = WE - T * (WE/WET)
        WT = WT - T * (WT/WET)
        WET = WE + WT
        IF (WET .LT. EPS) THEN
          WE = 0.00
          WT = 0.00
        END IF
      END IF
C
C     DRAIN WATER ABOVE FIELD CAPACITY FROM THE TRANSPIRATION ZONE
C     (AFTER TRANSPIRATION).
C
      IF (WT .GE. WTP) THEN
        EX2 = WT-WTP
        WT = WTP
        WE = WE+EX2
        IF (WE .GE. WEP) THEN
          WE = WEP
        END IF
      END IF
C
C *** CUMULATE STAGE ET
C
      ETPO(ISTG)=ETPO(ISTG)+PET
      ETAC(ISTG)=ETAC(ISTG)+T+E
      RETURN
      END
C     *******************************************************************
C
      SUBROUTINE PROFT(CROP,IRSG,MONEY)
C
C     *******************************************************************
      INTEGER CROP,MKMND,TODAY,YEARTH
      DIMENSION XXS(10),YYC(10)
$INSERT NAMCM1
C
C *** ESTIMATE YIELD AND GROSS RETURN
C
      DO 50 J=1,6
        XXS(J)=XXSOW(CROP,J)
        YYC(J)=YYILD(CROP,J)
```

```
   50 CONTINUE
C
      FRACT=1.0
      DO 100 I=1,4
        FRACT=FRACT*(ETAC(I)/ETPO(I))**CS(CROP,I)
  100 CONTINUE
C
      DAY=FLOAT(JULN(MKMND))
      PYDFC=TABEX(YYC,XXS,DAY,6)
      YIELD=STD(1,CROP)*PYDFC*FRACT
      REVEN=YIELD*PRICE(IIRUN,CROP)
C
C *** IRRIGATION COST DEPENDENT ON IRRIGATION SYSTEM AND DEPTH
C
      DPIRR=DPIRR/2.54
      CSTIR=UIRCS(IRSYS,IRSG)*DPIRR*2.46
C
C *** NET RETURN
C
      TLCST=PDCST(CROP)+CSTIR
      PROFT=REVEN-TLCST
C
C *** CALCULATE NET DISCOUNT RETURN
C
      YEARTH=INT(TODAY/365)
      MONEY=PROFT/((1.+DEPRE)**YEARTH)
C     WRITE (1,30) CROP,FRACT,REVEN,PDCST(CROP),CSTIR,DPIRR,MONEY
C  30 FORMAT(I2,5(1X,F8.3),I5)
      RETURN
      END
C     *****************************************************************
C
      SUBROUTINE SORT(NNEW)
C
C     *****************************************************************
      INTEGER X(40),Y(40),TEMP,FROM,TO
$INSERT NAMCM2
C
      DO 50 I=1,NNEW
        X(I)=IH(I)
        Y(I)=ISW(I)
   50 CONTINUE
C
      NM1=NNEW-1
      DO 200 I=1,NM1
        IP1=I+1
        DO 100 J=IP1,NNEW
          IF (X(I) .LE. X(J)) GOTO 100
          TEMP=X(I)
          X(I)=X(J)
          X(J)=TEMP
          TEMP=Y(I)
          Y(I)=Y(J)
          Y(J)=TEMP
```

```
  100   CONTINUE
  200 CONTINUE
C
      DO 300 I=1,NNEW
        INDEX(I)=NEW(X(I),Y(I))
  300 CONTINUE
      RETURN
      END
C     *****************************************************************
C
      SUBROUTINE ORDER(NEXT,NNEW)
C
C     *****************************************************************
C *** SEQUENTIAL NUMBERING SCHEME FOR NETWORK NODES
C
      INTEGER ARC,FROM,TO
$INSERT NAMCM2
C
      IF (IH(INDEX(1)) - IP(NODES)) 300,300,100
C
C *** APPEND NEW NODES TO THE LIST
C
  100 INI=1
      GOTO 200
  150 INI=I
  200 DO 250 I=INI,NNEW
        ARC=ARC+1
        NODES=NODES+1
        II=INDEX(I)
        IP(NODES)=IH(II)
        IW(NODES)=ISW(II)
        NODE(IP(NODES),IW(NODES))=NODES
        JC(NEXT,NODES)=IC(II)
        JG(NEXT,NODES)=IG(II)
        JS(NEXT,NODES)=IS(II)
        JR(NEXT,NODES)=IR(II)
        FROM(ARC)=NEXT
        TO(ARC)=NODES
  250 CONTINUE
      RETURN
C
C *** INSERT NEW NODES TO EXISTENT NODE SEQUENCE
C *** SEARCH FOR CORRECT INSERTION FROM THE BOTTOM OF THE LIST
C
  300 CONTINUE
      DO 600 I=1,NNEW
        II=INDEX(I)
        DO 350 J=NODES,1,-1
          IF (IH(II) .GE. IP(J)) GOTO 400
  350   CONTINUE
  400   IF (NODE(IH(II),ISW(II)) .NE. 0) GOTO 550
        IF (J .GE. NODES) GOTO 150
C
C *** NODE NOT YET BEEN NUMBERED
```

```
C *** FIRST, UPDATE INFORMATION OF OLD NODES AND ARCS
C
        LOCATE=J+1
        DO 500 K=NODES,LOCATE,-1
          K1=K+1
          IP(K1)=IP(K)
          IW(K1)=IW(K)
          NODE(IP(K1),IW(K1))=K1
          DO 450 L=ARC,1,-1
            NNALT=0
            IF (TO(L) .NE. K) GOTO 450
            M=FROM(L)
            JC(M,K1)=JC(M,K)
            JG(M,K1)=JG(M,K)
            JS(M,K1)=JS(M,K)
            JR(M,K1)=JR(M,K)
            TO(L)=K1
C           NNALT=NNALT+1
C           IF (NNALT .GT. 120) GOTO 500
  450     CONTINUE
  500   CONTINUE
C
C *** SECOND, NEW NODE IS INSERTED
C
        NODES=NODES+1
        IP(LOCATE)=IH(II)
        IW(LOCATE)=ISW(II)
        NODE(IP(LOCATE),IW(LOCATE))=LOCATE
        JC(NEXT,LOCATE)=IC(II)
        JG(NEXT,LOCATE)=IG(II)
        JS(NEXT,LOCATE)=IS(II)
        JR(NEXT,LOCATE)=IR(II)
        ARC=ARC+1
        FROM(ARC)=NEXT
        TO(ARC)=LOCATE
        GOTO 600
C
C *** NODE HAS BEEN NUMBERED
C
  550   NUMBR=NODE(IH(II),ISW(II))
        JC(NEXT,NUMBR)=IC(II)
        JG(NEXT,NUMBR)=IG(II)
        JS(NEXT,NUMBR)=IS(II)
        JR(NEXT,NUMBR)=IR(II)
        ARC=ARC+1
        FROM(ARC)=NEXT
        TO(ARC)=NUMBR
  600 CONTINUE
C
      RETURN
      END
```

```
C     ******************************************************************
C
      SUBROUTINE LISTN
C
C     ******************************************************************
      INTEGER ARC,FROM,TO,TEMP
$INSERT NAMCM1
$INSERT NAMCM2
C
      CALL OPENF(IOU1,'NETWOK',6,40,0,1,2,3,IC)
C
      NM1=ARC-1
      DO 100 I=1,NM1
        IP1=I+1
        DO 50 J=IP1,ARC
          IF (TO(I) .LE. TO(J)) GOTO 50
          TEMP=TO(I)
          TO(I)=TO(J)
          TO(J)=TEMP
          TEMP=FROM(I)
          FROM(I)=FROM(J)
          FROM(J)=TEMP
   50   CONTINUE
  100 CONTINUE
C
      DO 200 I=1,ARC
        M=FROM(I)
        N=TO(I)
        WRITE(IOU1,900) M,N,JR(M,N),IP(M),IW(M),JC(M,N),JG(M,N),
     $                  JS(M,N)
  200 CONTINUE
C
      CALL CLOSE(IOU1,IC)
      RETURN
  900 FORMAT(12X,8I5)
C
      END
C     ******************************************************************
C
      SUBROUTINE KPATH
C
C     ******************************************************************
C     A DESCRIPTION OF THE NETWORK IS READ IN.  THE NETWORK MUST BE
C     SORTED IN INCREASING ORDER BY ARC ENDING NODE NUMBER.  MOREOVER,
C     IT IS ASSUMED THAT THE NODES ARE NUMBERED CONSECUTIVELY FROM 1
C     TO N.  ALSO THE NETWORK SHOULD CONTAIN NO SELF-LOOPS AND ALL
C     CIRCUITS IN THE NETWORK ARE REQUIRED TO HAVE POSITIVE LENGTHS.
C     (APAPTED FROM D. R. SHIER, 1974)
C
C     THE VARIABLES AND ARRAYS IN COMMON ARE
C
C     NODES = THE NUMBER OF NODES IN THE NETWORK.
C     START = AN ARRAY WHOSE J-TH ELEMENT INDICATEDS THE FIRST
```

```
C             POSITION ON INC WHERE NODES INCIDENT TO NODE J ARE LISTED.
C      INC    = AN ARRAY CONTAINNING NODES I WHICH ARE INCIDENT TO NODE
C             J, LISTED IN ORDER OF INCREASING J.
C      VAL    = AN ARRAY CONTAINING THE ARC LENGTH VALUES CORRESPONDING
C             TO ARCS IN INC.
C      XV     = A TWO DIMENSIONAL ARRAY CONTAINING THE KTH LONGEST LABEL
C             OF THE NODE I.
C
C      VARIABLES WHOSE VALUES MUST BE SPECIFIED BY THE USER ARE
C
C      KL     = THE NUMBER OF DISTINCT PATH LENGTHS REQUIRED.
C      NS,NF  = THE INITIAL AND FINAL NODES OF ALL K LONGEST PATHS TO
C             BE GENERATED.
C
      INTEGER START,VAL,INC,XV,A(300)
$INSERT NAMCM1
$INSERT NAMCM2
C
      CALL OPENF(IOU1,'NETWOK',6,40,0,1,2,3,IC)
C
      INF=-999
C
C      AS THE NETWORK IS READ IN, THE VARIABLES AND ARRAYS NEEDED
C      BY LABELING PROCEDURE AND TRACE SUBROUTINE ARE CREATED.
C
      J=0
      NOW=1
   10 J=J+1
      READ (IOU1,15,END=30) NB,NA,LEN
   15 FORMAT(12X,3I5)
      IF (NA .GT. NODES) NODES=NA
      IF (NB .GT. NODES) NODES=NB
C
      NUW=NA
      IF (NUW .EQ. NOW) GOTO 20
      START(NA)=J
   20 INC(J)=NB
      VAL(J)=LEN
      NOW=NA
      GOTO 10
   30 START(NODES+1)=J
C
C      INITIALIZATION PHASE
C
      DO 40 I=1,NODES
        DO 35 J=1,KL
          XV(I,J)=INF
   35   CONTINUE
   40 CONTINUE
      XV(NS,1)=0
      I=NS
C
C      START ALGORITHM
C
```

```
   50 I=I+1
C
C     INITIALIZE A TO THE CURRENT K LONGEST PATH LENGTHS FOR NODE I,
C     IN STRICTLY DECREASING ORDER.
C
      DO 60 J=1,KL
        A(J)=XV(I,J)
   60 CONTINUE
      MIN=A(KL)
C
C     EACH NODE OF INC INCIDENT TO NODE I IS EXAMINED.
C
      IIS=START(I)
      IFIN=START(I+1)-1
      DO 200 L=IIS,IFIN
        II=INC(L)
        IV=VAL(L)
C
C     TEST TO SEE WHETHER IXV IS TOO SMALL TO BE INSERTED INTO A
C
        DO 180 M=1,KL
          IX=XV(II,M)
          IF (IX .LE. INF) GOTO 200
          IXV=IX+IV
          IF (IXV .LE. MIN) GOTO 200
C
C     IDENTIFY THE POSITION INTO WHICH IXV CAN BE INSERTED
C
          DO 110 J=KL,2,-1
            IF (IXV-A(J-1)) 120,180,110
  110     CONTINUE
          J=1
  120     JJ=KL
  150     IF (JJ .LE. J) GOTO 160
          A(JJ)=A(JJ-1)
          JJ=JJ-1
          GOTO 150
  160     A(J)=IXV
          MIN=A(KL)
  180   CONTINUE
  200 CONTINUE
C
C     UPDATE THE K LONGEST PATH LENGTHS TO NODE I.
C
      DO 250 J=1,KL
        XV(I,J)=A(J)
  250 CONTINUE
C
C     HAVE ALL NODES BEEN LABELLED ?
C
      IF (I .NE. NODES) GOTO 50
C
C     THE K LONGEST PATH LENGTHS FROM NODE NS TO NODE NF ARE DETERMINED.
C
```

```
      CALL TRACE
C
      CALL CLOSE(IOU1,IC)
C
      RETURN
      END
C     ******************************************************************
C
      SUBROUTINE TRACE
C
C     ******************************************************************
C  THIS SUBROUTINE WILL TRACE OUT THE PATHS CORRESPONDING TO THE K
C  DISTINCT LONGEST PATH LENGTHS FROM NODE NS TO NODE NF.  AT MOST PMAX
C  SUCH PATHS WILL BE GENERATED.  IT IS ASSUMED THAT ALL CITCUITS IN
C  THE NETWORK HAVE POSITIVE LENGTH.  MOREOVER ONLY PATHS HAVING AT
C  MOST 50 ARCS WILL BE PRODUCED.
C
C     VARIABLES DEFINED
C
C     NS,NF = THE INITIAL AND FINAL NODES OF ALL K LONGEST PATHS BEING
C              GENERATED.
C     PMAX  = THE MAXIMUM NUMBER OF PATHS TO BE GENERATED BETWEEN NODE
C              NS AND NF.
C     JJ    = INDEX OF THE PATH LENGTH FROM NS TO NF BEING EXPLORED.
C              JJ CAN TAKE ON VALUES FROM 1 TO K.
C     NP    = THE NUMBER OF PATHS FROM NS TO NF FOUND.
C     KK    = CURRENT POSITION OF LIST P.
C     P     = AN ARRAY CONTAINING NODES ON A POSSIBLE PATH FROM NS TO
NF.
C     Q     = AN ARRAY WHOSE I-TH ELEMENT GIVES THE POSITION, RELATIVE
C              TO START, OF NODE P(I) ON THE INC LIST FOR P(I-1).
C     PV    = AN ARRAY WHOSE I-TH ELEMENT IS THE ARC LENGTH EXTENDING
C              FROM NODE P(I) TO NODE P(I-1).
C     H     = AN ARRAY WHOSE I-TH ELEMENT IS TOTAL NUMBER OF NODES OF
THE
C              I-TH BEST PATH.
C
      INTEGER P(50),Q(50),PV(50),PMAX,H,CO,C
      INTEGER START,VAL,INC,XV
$INSERT NAMCM1
$INSERT NAMCM2
C
      CALL OPENF(IOU2,'CROPIN',6,66,0,1,2,3,IC)
C
C     INITIALIZATION PHASE
C
      PMAX=20
      INF=-999
      DO 10 I=1,50
        P(I)=0
        Q(I)=0
        PV(I)=0
   10 CONTINUE
C
```

```
      JJ=1
      IF (NS .EQ. NF) JJ=2
      NP=0
C     IF (XV(NF,JJ) .GT. INF) GOTO 15
C     WRITE (IOU2,909) NS,NF
C 909 FORMAT(1H1,'THERE ARE NO PATHS FROM NODE',I4,' TO NODE',I4)
C     GOTO 200
C
C  15 WRITE (IOU2,901) NS,NF
  901 FORMAT(1H ,'THE K LONGEST PATHS FROM NODE',I4,' TO NODE',I4//
     $        1H ,'PATH   LENGTH   NODE SEQUENCE'//)
C
C     THE JJ-TH DISTINCT PATH LENGTH IS BEING EXPLORED.
C
   20 KK=1
      LAB=XV(NF,JJ)
      IF (LAB .LE. INF) GOTO 200
      LL=LAB
      P(1)=NF
      CO=0
   30 LAST=0
C
C     NODES INCIDENT TO NODE P(KK) ARE SCANNED.
C
   40 NT=P(KK)
      IIS=START(NT)
      DO 45 ND=NT,NODES
        IF (START(ND+1) .NE. 0) GOTO 48
   45 CONTINUE
C
   48 IIF=START(ND+1)-1
      II=IIS+LAST
C  50 IF (II .GT. IIF) GOTO 90
   50 NI=INC(II)
      NV=VAL(II)
      LT=LAB-NV
C
C     TEST MADE, SEE IF THE CURRENT PATH CAN BE EXTENDED BACK TO NODE NI
C
      DO 60 J=1,KL
        IF (XV(NI,J)-LT) 70,80,60
   60 CONTINUE
   70 II=II+1
      GOTO 50
C
   80 KK=KK+1
C
C     ----------------------------------------------------------------
C     THIS PORTION ADDED TO EXCLUDE SEQUENCES OF PEANUT REPETITION IN
C     SUMMER.                                            5/29/85  TSAI
C
      C=JC(NI,NT)
C     WRITE (1,801) C,NI,NT
C 801 FORMAT(3I5)
```

```
      IF (C.LE.MXCRP .AND. C.NE.5) THEN
        IF (C .EQ. 6) THEN
          IF (CO .EQ. 6) THEN
            GOTO 160
          ELSE
            CO=C
          END IF
        ELSE
          CO=C
        END IF
      END IF
C     WRITE (1,802) C,CO,MXCRP
C 802 FORMAT(3I10)
C    ----------------------------------------------------------------
C
      IF (KK .GT. 50) GOTO 190
      P(KK)=NI
      Q(KK)=II-IIS+1
      PV(KK)=NV
      LAB=LT
C
C     TESTS MADE TO SEE IF THE CURRENT PATH CAN BE EXTENDED FURTHER.
C
      IF (LAB .NE. 0) GOTO 30
      IF (NI .NE. NS) GOTO 30
C
C     COMPLETE PATH FROM NS TO NF HAS BEEN GENERATED
C
      NP=NP+1
      H(JJ)=KK
      WRITE (IOU2,902) JJ,LL,(P(J),J=KK,1,-1)
  902 FORMAT(I3,I5,30I4)
C
C     ----------------------------------------------------------------
C     THIS PORTION IS COMMENTED OUT IN ORDER NOT TO DUPLICATE PATHS
C     OF THE SAME LENGTH.                                  5/15/85  TSAI
C
C     IF (NP .GE. PMAX) GOTO 200
C  90 LAST=Q(KK)
C     P(KK)=0
C     LAB=LAB+PV(KK)
C     KK=KK-1
C     IF (KK .GT. 0) GOTO 40
C     ----------------------------------------------------------------
C
C     EXPLORATION OF THE CURRENT JJ-TH DISTINCT PATH LENGTH IS ENDED.
C
  160 JJ=JJ+1
      IF (JJ .GT. KL) GOTO 200
      GOTO 20
C
  190 WRITE (IOU2,903)
  903 FORMAT(1H0,'NUMBER OF ARCS IN PATH EXCEEDS 50')
C
```

```
  200 CONTINUE
      CALL CLOSE(IOU2,IC)
C
      RETURN
      END
C     *****************************************************************
C
      SUBROUTINE DCODE
C
C     *****************************************************************
$INSERT NAMCM1
$INSERT NAMCM2
C
      INTEGER P(50),H,C,G,S,R,YEAR,AR,ARC
      INTEGER RMON,VAR(7,2),SGY(4,3),SENS(21)
C
      DATA VAR/'F.S.','S.S.','BRAG','WAYN','WHEA','PEAN','IDLE',
     $         'CORN','CORN','G   ','E   ','T301','UT  ','    '/
      DATA SGY/'RAIN','FREQ','INFR','****','-FED','UENT','EQUE',
     $         '    ','    ','    ','NT  ','    '/
      DATA SENS/'D.01','D.02','D.03','D.04','D.05','D.06','D.07',
     $          'D.08','D.09','D.10','D.11','D.12','D.13','D.14',
     $          'D.15','D.16','D.17','D.18','D.19','D.20','D.21'/
C
      NFILE=MXRUN*(IIWEA-1)+IIRUN
      CALL OPENF(IOU2,'CROPIN',6,66,0,1,2,3,IC)
      CALL OPENF(IOU4,SENS(NFILE),4,40,0,1,2,3,IC)
C
      IF (NFILE .LE. 1) THEN
        CALL OPENF(IOU3,'SERIES',6,40,0,1,2,3,IC)
      END IF
C
      WRITE (1,90) NFILE,NODES,ARC
      WRITE (IOU3,900)
      WRITE (IOU3,910) NFILE,(WFILE(I),I=1,2),
     $                 (PRICE(IIRUN,J),J=1,MXCRP)
C
      JCOUN=0
  100 READ (IOU2,110,END=300) NP,LL,(P(J),J=1,H(NP))
C
      JCOUN=JCOUN+1
      IF (JCOUN.LE.5 .AND. NP.LE.KL) THEN
C     IF (MOD(NP,5) .EQ. 1) THEN
      WRITE (IOU3,930) NP,LL
      WRITE (IOU3,940)
      JJ=0
  150 JJ=JJ+1
      IF (P(JJ) .NE. NF) THEN
        M=P(JJ)
        YEAR=INT(IP(M)/365)+1
        JULD=MOD(IP(M),365)
        CALL NAILUJ(JULD,RMON,NDAY)
        N=P(JJ+1)
        C=JC(M,N)
```

```
        G=JG(M,N)
        S=JS(M,N)
        R=JR(M,N)
        IF (C .NE. 0) THEN
          WRITE (IOU3,200) RMON,NDAY,YEAR,IW(M),(VAR(C,J),J=1,2),G,
     $                    (SGY(S,J),J=1,3),R
  200     FORMAT(11X,A3,'-',I2,'-',I1,3X,I2,'%',3X,2A4,3X,I3,2X,3A4,4X,
     $           I4)
          GOTO 150
        ELSE
          WRITE (IOU3,250) RMON,NDAY,YEAR,IW(M)
  250     FORMAT(11X,A3,'-',I2,'-',I1,3X,I2,'%',3X,4(1H*),7X,3(1H*),2X,
     $           4(1H*),13X,'***')
          WRITE (IOU3,920)
        END IF
      END IF
C     END IF
      GOTO 100
      END IF
C
  300 IF (IIWEA.LT.MXYER .OR. IIRUN.LT.MXRUN) THEN
        CALL CLOSE(IOU2,IC)
        CALL CLOSE(IOU4,IC)
      ELSE
        CALL CLOSE(IOU2,IC)
        CALL CLOSE(IOU3,IC)
        CALL CLOSE(IOU4,IC)
      END IF
      RETURN
C
   90 FORMAT('NFILE= ',I2,' NODES= ',I4,' ARCS=',I5)
  110 FORMAT(I3,I5,30I4)
  900 FORMAT(1H1,///,11X,'***  OPTIMAL SEQUENCING OF MULTICROPPING SYSTE
     $MS  ***',/)
  910 FORMAT(11X,'RUN #',I2,26X,'WEATHER FILE: ',2A4,/
     $11X,'CROP PRICE ($/KG)=',F5.3,5F6.3/)
  920 FORMAT(1H1,//,11X,'<CONTINUED>'/)
  930 FORMAT(11X,'SEQUENCE',I4,' HAVING TOTAL NET DISCOUNTED RETURN $',
     $I4,/)
  940 FORMAT(11X,'DECISION INITIAL',10X,'SEASON IRRIGATION  DISCOUNT',/
     $13X,'DATE     S.W.  CULTIVAR (DAYS)  STRATEGY    RETURN',/
     $11X,8(1H_),1X,7(1H_),1X,8(1H_),1X,6(1H_),1X,10(1H_),2X,
     $8(1H_),/)
      END
C     ******************************************************************
C
      SUBROUTINE ETBARE
C
C     ******************************************************************
      INTEGER TODAY,SW1

      LOGICAL FIRST
$INSERT NAMCM1
      DATA DEV/10./,DRZ/30./,ALFA/0.234/,EPS/0.00001/
```

```
      DATA THETWP/4.4894E-02/,THETFC/10.00E-02/
C
      IF (FIRST) THEN
C
C *** INITIALIZE PARAMETERS FOR CURRENT SEASON
C
        ORISW=FLOAT(SW1)/100.
        DDRY = 0.
        WCMAX=THETFC-THETWP
        WCAVL=ORISW-THETWP
        THETAC=THETWP+0.5*WCMAX
        WEP = DEV * WCMAX
        WE = DEV * WCAVL
        WTP = DRZ * WCMAX
        WT = DRZ * WCAVL
      END IF
      FIRST=.FALSE.
C
      N=TODAY
C
C *** CALCULATE POTENTIAL ET (PET) USING PENMAN EQUATION
C
      XLAI = 0.25
      CALL PENMAN(XLAI,PET,EP)
C
C *** CALCULATE POTENTIAL TRANSPIRATION RATE (RITCHIE, 1972)
C
C     IF (XLAI .LT. 0.1) TP=0.00001
C     IF (XLAI.GE.0.1 .AND. XLAI.LE.3.0) TP=PET*(0.7*SQRT(XLAI)-0.21)
C     IF (XLAI .GT. 3.0) TP=PET
      TP=PET*(0.7*SQRT(XLAI)-0.21)
C
C     THE FOLLOWING ADDED FOR SOIL FLUX TERM
C
      IF (WT/WTP .LT. 0.2) WT = WT+0.05
C
C *** CALCULATE TRANSPIRATION RATE, T
C
      WET1 = WE + WT
      THETA = THETWP+WET1/(DEV+DRZ)
      IF (THETA .GE. THETAC) THEN
        T = TP
      ELSE
        T = TP * (THETA-THETWP)/(THETAC-THETWP)
      END IF
C
C *** CALCULATE EVAPORATION RATE ,  E
C
      EP = AMIN1(AMAX1(0.00001,(PET-T)),EP)
C
C     TWO-STAGE EVAPORATION PROCESS
C
      IF (RAIN(N) .GE. EPS) THEN
        DDRY = 0.
```

```
        E = EP
      ELSE
        DDRY = DDRY +1
        E = ALFA*(SQRT(DDRY)-SQRT(DDRY-1))
        IF ( E .GT. EP) THEN
          E = EP
        END IF
      EN DIF
C
C *** UPDATE SOIL WATER STATUS
C
C     RAINFALL
C
      IF (RAIN(N) .GE. EPS) THEN
        WE = WE + RAIN(N)
        IF (WE  .GE.  WEP)  THEN
          WT = WT + WE - WEP
          WE = WEP
        END IF
      END IF
C
C     EVAPORATION ZONE
C
      IF (E .GT. WE) E = WE
      WE = WE - E
C
C     TRANSPIRATION ZONE
C
      WET = WE + WT
      IF (WET .LT. EPS) THEN
C
C     DO NOT LET SOIL WATER CONTENTS DECREASE BELOW PWP
C     (IF SOIL WATER DROPS BELOW ZERO, DRAW ON TRANSIENT WATER,
C     AND RESET THE WATER CONTENTS TO ZERO.)
C
        WE = 0.00
        WT = 0.00
      ELSE
        WE = WE - T * (WE/WET)
        WT = WT - T * (WT/WET)
        WET = WE + WT
        IF (WET .LT. EPS) THEN
          WE = 0.00
          WT = 0.00
        END IF
      END IF
C
C     DRAIN WATER ABOVE FIELD CAPACITY FROM THE TRANSPIRATION ZONE
C     (AFTER TRANSPIRATION).
C
      IF (WT .GE. WTP) THEN
        EX2 = WT-WTP
        WT = WTP
        WE = WE+EX2
```

```
        IF (WE .GE. WEP) THEN
          WE = WEP
        END IF
      END IF
C     WRITE (1,991) DDRY,WE,WT,PET,EP,TP,E,T,THETA
  991 FORMAT(F3.0,10(1X,F6.3))
C
      RETURN
      END
C     ****************************************************************
C
      SUBROUTINE WCALC(PHTFCT,PHTFCY)
C
C     ****************************************************************
C     THIS SUBROUTINE CALCULATES HOURLY TEMPERATURES AND TEMPERATURE
C     FACTOR FOR USE IN PHENOLOGICAL STAGE CALCULATIONS
C
      INTEGER TODAY
      DIMENSION THR(24),PHTFCT(24),PHTFCY(24)
$INSERT NAMCM1
C
      N=TODAY
      IF (TODAY .EQ. 1) GOTO 200
      DO 100 IXX=1,24
        PHTFCY(IXX)=PHTFCT(IXX)
  100 CONTINUE
  200 CONTINUE
C
C     THIS SECTION CALCULATES HOURLY TEMPERATURES FOR THE DAY
C
            DO 600 IXX = 1,24
            X = IXX
            IF (X .LT. SNUP(N) + 2.0) GO TO 400
            IF (X .GT. SNDN(N)) GO TO 300
C
C     SINE CURVE
C
            TAU = 3.1417 * (X-SNUP(N)-2.)/(SNDN(N)-SNUP(N))
            THR(IXX) = TMIN(N) + ((TMAX(N)-TMIN(N)) * SIN(TAU))
            GO TO 600
C
C     AFTER SUNSET BEFORE MIDNIGHT
C
  300       TAU = 3.1417 * (SNDN(N)-SNUP(N)-2.)/(SNDN(N)-SNUP(N))
            TLIN = TMIN(N) + ((TMAX(N)-TMIN(N)) * SIN(TAU))
            HDARK = 24. - SNDN(N) + SNUP(N+1) + 2.
            SLOPE = (TLIN - TMIN(N+1)) / HDARK
            THR(IXX) = TLIN - (SLOPE * (X - SNDN(N)))
            GO TO 600
C
C     BETWEEN MIDNIGHT AND SUNRISE + 2 HRS.
C
  400       CONTINUE
            IF (N .EQ. 1) GO TO 500
```

```
          TAU = 3.1417 * (SNDN(N-1)-SNUP(N-1)-2.)/(SNDN(N-1)-SNUP(N-1))
          TLIN = TMIN(N-1) + ((TMAX(N-1) - TMIN(N-1)) * SIN(TAU))
          HDARK = 24. - SNDN(N-1) + SNUP(N) + 2.
          SLOPE = (TLIN - TMIN(N)) / HDARK
          THR(IXX) = TLIN - SLOPE * (X + 24. - SNDN(N-1))
          GO TO 600
  500     CONTINUE
C
C         IF THIS IS DAY ONE OF SIMULATION THEN AVERAGE OF MAX AND MIN
C         TEMPERATURE FOR THE DAY IS USED IN COMPUTING THE HOURLY TEMPS
C         IN ORDER TO AVOID THE PROBLEM OF N-1 BEING ZERO IN THE
C         ABOVE CALCULATIONS.
C
          THR(IXX) = (TMAX(N) + TMIN(N)) / 2.0
  600     CONTINUE
C
C     COMPUTE TEMPERATURE FACTORS FOR EACH HOUR FOR USE IN PHENOLOGICAL
C     CALCULATIONS
C
          DO 700 IXX = 1,24
          IF (THR(IXX) .LE. TOPT) PHTFCT(IXX) = PHCON3 * THR(IXX) +
     +        PHCON4
          IF (THR(IXX) .GT. TOPT) PHTFCT(IXX) = PHCON5 * THR(IXX) +
     +        PHCON6
          PHTFCT(IXX) = AMAX1(0.0,PHTFCT(IXX))
  700     CONTINUE
      RETURN
      END
C     ****************************************************************
C
      SUBROUTINE PENMAN(XLAI,PET,EP)
C
C     ****************************************************************
C *** CALCULATE POTENTIAL ET (PET) & POTENTIAL SOIL EVAPORATION (EP)
C *** USING PENMAN EQUATION (IFAS ET BULLETIN, 1981)
C
C     XLAI = LEAF AREA INDEX OF THE DAY (NNDAY)
C     ESUBD = DEWPOINT VAPOR PRESSURE (MILLIBARS)
C     VPD = VAPOR PRESSURE DEFICIT (MILLIBARS)
C     DELTA = SLOPE OF SATU. VAPOR PRESSURE CURVE AT MEAN AIR TEMP.
C     GAMMA = CONSTANT OF THE WET AND DRY BULB PSYCHROMETER EQN.
C     GAMMA = .0006595 * BARAMETRIC PRESSURE (MILLIBARS)
C     XLAMDA = LATENT HEAT OF VAPORIZATION OF H2O (CAL CM-2 MM)
C     RSO = CLEAR SKY RADIATION (LANGLEY/DAY)
C     RN = NET RADIATION (LANGLEY/DAY)
C
      INTEGER TODAY
$INSERT NAMCM1
      DATA AS/.15/,ACROP/.25/,GAMMA/.66/,XLAMDA/58.4/,XLAT/0.61987/
C
      N=TODAY
      ALPHA2 = AS+.25*(ACROP-AS)*XLAI
      ALPHA2 = AMIN1(ALPHA2,ACROP)
      TC = (TMAX(N)+TMIN(N))/2.0
```

```
      TK = TC+273.
C
      ESUBD = 33.8639*((.00738*TMIN(N)+.8072)**8-.000019*(1.8*TMIN(N)+
     $        48.)+0.001316)
C
      DELTA = 33.8639*((.05904*(.00738*TC+.8072)**7)-.0000342)
C
      VPD = 16.932*((.00738*TC+.8072)**8-(.00738*TMIN(N)+.8072)**8-
     $      .000019*(1.8*(TC-TMIN(N))))
C
      RSO = RADCL(JULN(N),XLAT)
      RN = (1.-ALPHA2)*XLANG(N)-(XLANG(N)/RSO*1.42-.42)*(.56-.08*SQRT
     $     (ESUBD))*11.71E-08*TK**4
C
C *** CHANGE FROM LANGLEYS TO MM H2O EVAPORATED.
C
      RNO = AMAX1(RN/XLAMDA,0.)
C
      EO = (DELTA/(DELTA+GAMMA))*RNO+.263*VPD*(.5+.0062*WIND(N))*(GAMMA/
     $     (GAMMA+DELTA))
C
      EP = (DELTA/(DELTA+GAMMA))*RNO
C
C *** CONVERT FROM MM TO CM.
C
      PET = 0.1*EO
      EP = 0.1*EP
      PET = AMAXI(PET,0.00001)
      EP = AMAX1(EP,0.00001)
      RETURN
      END
C     ****************************************************************
C
      FUNCTION RADCL(JDAY,XLAT)
C
C     ****************************************************************
C     THIS FUNCTION ESTIMATES CLEAR-SKY INSOLATION AT THE SURFACE OF
C     THE EARTH BY CALCULATING EXTRATERRESTRIAL SOLAR RADIATION AS
C     A FUNCTION OF LATITUDE AND JULIAN DATE, AND REDUCING THIS VALUE
C     BY 20% TO ACCOUNT FOR AVERAGE CLEAR-SKY ATTENUATION. ATTENUATION
C     ESTIMATES ARE TO BE IMPROVED IN FUTURE VERSIONS.
C     (SEE ASCE REPORT "Consumptive Use of Water and Irrigation Water
C       Requirements, M. E. Jensen, Ed., 1973, & HANDBOOK OF
C       METEOROLOGY, F. A. Berry, E. Bollay, and N. R. Beers, eds.,
C       McGraw Hill, 1945)
C
C     XLAT=LATITUDE OF USER'S LOCATION (RADIANS, NORTHERN HEMISPHERE
C     JDAY=JULIAN DATE
C     SC=SOLAR CONSTANT (CAL CM-2 HR-1, ASSUMING 1.94 CAL CM-2 MIN-1
C     RADCL=CLEAR-SKY RADIATION, CAL CM-2 DAY-1
C
      PI = 3.141593
      ATTFAC = .804
      SC = 116.40
```

```
C
C     DFAC=VARIATION IN RADIATION DUE TO VARIATION IN ORBITAL RADIUS
C
      RM = 1.
      RADIUS = RM*(1.-(0.01673*COS(2.0*PI*JDAY/365.)))
      DFAC = (RM/RADIUS)**2
C
      DECLIN = PI*(23.47/180.)*SIN(2.0*PI*(284+JDAY)/365.)
      COSZA = (COS(DECLIN+XLAT)-COS(XLAT-DECLIN))/(COS(XLAT+DECLIN)+COS
     $     (XLAT-DECLIN))
C
C     CALCULATE ARCCOS OF THE COSINE OF ZENITH ANGLE
C     (TO OBTAIN HOUR ANGLE OF SUNRISE & SUNSET)
C
      IF (ABS(COSZA) .LE. 0.00001) GO TO 100
      ARG = ABS(1.0-COSZA**2)
      A = SQRT(ARG)
      HASUN = ATAN(A/COSZA)
      IF (COSZA .GT. 0.0) GO TO 200
      HASUN = PI+HASUN
      GO TO 200
  100 HASUN = PI/2.0
  200 CONTINUE
C
      ACRIT = PI/2.
      IF (XLAT-DECLIN .GE. ACRIT) GO TO 300
C
      RADCL = ATTFAC*DFAC*(24./PI)*SC*(HASUN*SIN(DECLIN)*SIN(XLAT)+SQRT
     $     (ABS(COS(DECLIN+XLAT))*COS(DECLIN-XLAT)))
C
      RETURN
  300 RADCL = 0.
      RETURN
      END
C     ******************************************************************
C
      SUBROUTINE NAILUJ(JULD,RMON,NDAY)
C
C     ******************************************************************
      INTEGER MON(12)
      LOGICAL*4 RNAME(12),RMON
      DATA MON/31,28,31,30,31,30,31,31,30,31,30,31/
      DATA RNAME/'JAN','FEB','MAR','APR','MAY','JUN','JUL','AUG',
     $  'SEP','OCT','NOV','DEC'/
C
      NSUM=0
      DO 100 JCOUNT=1,12
        NDIF=JULD-NSUM
        IF (NDIF .LE. MON(JCOUNT)) GOTO 200
        NSUM=NSUM+MON(JCOUNT)
  100 CONTINUE
      GOTO 300
C
  200 NDAY=NDIF
```

```
      RMON=RNAME(JCOUNT)
C
  300 RETURN
      END
C     ******************************************************************
C
      FUNCTION TABEX(VAL,ARG,DUMMY,K)
C
C     ******************************************************************
      DIMENSION VAL(20),ARG(20)
      DO 101 J=2,K
      IF (DUMMY .GT. ARG(J)) GOTO 101
      GOTO 102
  101 CONTINUE
      J=K
  102 TABEX=(DUMMY-ARG(J-1))*(VAL(J)-VAL(J-1))/(ARG(J)-ARG(J-1))+
     $       VAL(J-1)
      RETURN
      END
C     ******************************************************************
C
      FUNCTION ISCRE(XX)
C
C     ******************************************************************
      XX=XX*100.
      IF (AMOD(XX,1.) .LE. 0.5) THEN
        ISCRE=INT(XX)
      ELSE
        ISCRE=INT(XX)+1
      END IF
      RETURN
      END
```

```
C      *************************************************************
C
       COMMON BLOCK
C
C      *************************************************************

       COMMON/SIMUL/ NNDAY,TODAY,MATUR,ISTG,ETPO(4),ETAC(4),THETA,
      $  DPIRR,NNMAX,MKMND,SW1,SW2,FIRST,WFILE(2),IIRUN,IIN1,IIN2,
      $  IIN3,IIN4,IOU1,IOU2,IOU3,IOU4,ICASH,10(10)
       COMMON/WEATR/ JULN(2190),TMAX(2190),TMIN(2190),SNUP(2190),
      $  SNDN(2190),XLANG(2190),WIND(2190),RAIN(2190)
       COMMON/FACTS/ IDDEC,MOIST,STD(10,8),PRICE(98,8),GASPC,DSLPC,
      $  WAGE,DEPRE,IRSYS,RATE(3),PDCST(8),UIRCS(4,3),LIDLE(3),MXCRP,
      $  MXRUN,MXYER,IIWEA
       COMMON/GROWS/ A0(5),A1(5),A2(5),B0(5),B1(5),B2(5),B3(5),B4(5),
      $  TNLG1(2),TNLG0(2),THVAR(2),DHVAR(2),PHCON1(2),PHCON2(2),TOPT,
      $  TPHMIN,TPHMAX,PHCON3,PHCON4,PHCON5,PHCON6,PHTHRS(2,11),
      $  XXLAI(8,11),YYLAI(8,11),XXROT(8,11),YYROT(8,11),HDGE(6,4),
      $  CS(8,4),XXSOW(8,10),YYILD(8,10),
       COMMON/NETWK/ IH(40),ISW(40),IC(40),IS(40),IR(40),INDEX(40),
      $  IG(40),JC(450,450),JG(450,450),JS(450,450),JR(450,450),
      $  (450),IW(450),NODE(2190,10),NEW(2190,10),FROM(2000),
      $  TO(2000)
       COMMON/LONGS/ NS,NF,KL,START(451),INC(2000),VAL(2000),
      $  XV(450,100),NODES,ARC,H(100)
```

APPENDIX C
INPUT FILE 'GROWS'

```
 38.7     45.1    66.3   81.4                         F.S.CORN (BENNETT 1982)
 33.6     40.7    57.7   70.4                         S.S.CORN
 27.3     42.4    68.2   97.3                         PEANUT (BOOTE, 1981)
0.0 8.41 10.93 10.94 24.38                            A0 (ROBERTSON,1969)
0.0 1.005 0.925 1.389 -1.14                           A1
0.0 0.0 -.06025 -.08191 0.0                           A2
44.37 43.64 42.65 42.18 37.67                         B0
.01086 .0003512 .002958 .0002458 .00006733            B1
-.000223 -.00000503 0.0 0.0 0.0                       B2
.009732 .0003666 .003943 .0003109 .00003442           B3
-.000227 -.00000428 0.0 0.0 0.0                       B4
30.0 7.0 45.0                                         TOPT,TPHMIN,TPHMAX
6.522 10.87 2.4 1.0 9.48                              PHTHRS(J),J=1,5
5.2 11.0 63.0 2.0                                     TNLG1,TNLG0,THVAR,DHVAR
3.0 20.35 12.13                                       THRVAR(J),J=1,3
0.14 0.16 0.575                                       VRFCR(J),J=1,3
5.2 9.5 32.0 2.0                                      TNLG1 TNLG0,THVAR,DHVAR
6.0 14.5 10.0                                         THRVAR(J),J=1,3
0.2 0.5 0.6                                           VRFCR(J),J=1,3
 40.  48.  58.  77.  90. 102. 115. 140.               XXSOW(1,J) (AGRO.FKS 117)
0.87 0.96 1.00 0.91 0.80 0.74 0.67 0.59               YYILD(1,J)
 40.  48.  58.  77.  90. 102. 125. 150.               XXSOW(2,J) (AGRO.FKS 117)
0.78 0.87 0.95 1.00 0.92 0.85 0.76 0.62               YYILD(2,J)
 75. 106. 136. 152. 166. 182. 197. 228.               XXSOW(3,J) (SOYGRO5.0)
0.80 0.89 0.94 1.00 0.92 0.87 0.81 0.73               YYILD(3,J)
 61.  91. 106. 121. 136. 166. 197. 228.               XXSOW(4,J) (SOYGRO5.0)
0.82 0.93 1.00 0.95 0.90 0.83 0.78 0.70               YYILD(4,J)
260. 275. 285. 300. 315. 330. 345. 366.               XXSOW(5,J)
0.78 0.92 0.95 1.00 0.98 0.90 0.82 0.73               YYILD(5,J)
 70.  85. 100. 112. 125. 140. 160. 190.               XXSOW(6,J)
0.76 0.91 0.95 1.00 0.90 0.82 0.76 0.70               YYILD(6,J)
0 34  48  60  69  76  90 110 118 133 180              XXLAI,F.S.CORN (BENNETT)
0 .6 1.1 2.4 3.2 3.7 4.0 2.8 1.9 0.7 0.0              YYLAI,
0 24  39  46  53  65  74  88 103 115 160              XXLAI,S.S.CORN (LOREN)
0 .4 2.4 3.9 4.1 3.8 3.7 3.3 1.4 0.4 0.0              YYLAI,
0 20  34  45  64  90 108 112 123 155 200              XXLAI,BRAGG (SOYGRO5.0)
0 .2 0.7 1.8 3.2 3.1 2.1 1.0 0.5 0.2 0.0              YYLAI
0 15  28  33  47  56  72  75  82 100 150              XXLAI,WAYNE (SOYGRO5.0)
0 .2 0.8 1.4 2.8 3.3 2.4 1.2 0.6 0.2 0.0              YYLAI
0 32  67 105 128 135 142 149 161 178 250              XXLAI,WHEAT (HODGES ET AL)
0 .5 0.8 1.4 1.9 3.6 4.0 3.8 2.3 0.3 0.0              YYLAI
0 35  49  63  70  77  84  91 105 126 160              XXLAI,PEANUT (MCGRAW)
0 .8 1.6 3.5 4.7 4.4 4.6 5.0 4.1 2.5 0.0              YYLAI
```

```
0 11  30  37  44  57  62  78  89 111 250    XXROT,CORN (HAMMOND,1981)
0 18  28  40  55 103 128 155 165 169 175    YYROT
0 10  28  46  50  53  83 128 156 200 250    XXROT,SOYBEAN
0 13  32  67  80  95 152 176 182 184 187    YYROT
0 12  40  70 118 132 170 182 195 205 250    XXROT,WHEAT (TEARS)
0  7  18  42  60  80 130 150 180 192 213    YYROT
0 10  28  46  50  53  83 128 156 200 250    XXROT,PEANUT
0 13  32  67  80  95 152 176 182 184 187    YYROT
0.371 2.021 1.992 0.475                     CS(I),F.S.CORN
0.371 2.021 1.992 0.475                     CS(I),S.S.CORN
0.698 0.961 1.034 0.690                     CS(I),BRAGG
0.698 0.961 1.034 0.690                     CS(I),WAYNE
0.065 0.410 0.114 0.026                     CS(I),WHEAT
0.578 1.032 1.531 0.627                     CS(I),PEANUT
```

APPENDIX D
INPUT FILE 'FACTS'

```
1 05 01 20                                        NS,KL,MXRUN,MXYER
075 10 6                                          IDDEC,MOIST,MXCRP
42 91 175                                         LIDLE(3)
1 0.0 0.4 0.6                                     IRSYS,RATE(I) (IN.)
346.2 346.2 308.2 308.2 248.9 481.2               PRODUCTION COST ($/HA)
1.30 1.45 4.5 0.12                                GASPC,DSLPC,WAGE,DEPRE
9800. 8600. 4680. 4010. 3680. 3180.               POTENTIAL YIELD (KG/HA)
0.103 0.103 0.238 0.238 0.137 0.473               CROP PRICE ($/KG)
0.083 0.083 0.238 0.238 0.137 0.473               CROP PRICE ($/KG)
0.093 0.093 0.238 0.238 0.137 0.473               CROP PRICE ($/KG)
0.113 0.113 0.238 0.238 0.137 0.473               CROP PRICE ($/KG)
0.123 0.123 0.238 0.238 0.137 0.473               CROP PRICE ($/KG)
0.103 0.103 0.190 0.190 0.137 0.473               CROP PRICE ($/KG)
0.103 0.103 0.214 0.214 0.137 0.473               CROP PRICE ($/KG)
0.103 0.103 0.262 0.262 0.137 0.473               CROP PRICE ($/KG)
0.103 0.103 0.285 0.285 0.137 0.473               CROP PRICE ($/KG)
0.103 0.103 0.238 0.238 0.110 0.473               CROP PRICE ($/KG)
0.103 0.103 0.238 0.238 0.123 0.473               CROP PRICE ($/KG)
0.103 0.103 0.238 0.238 0.151 0.473               CROP PRICE ($/KG)
0.103 0.103 0.238 0.238 0.164 0.473               CROP PRICE ($/KG)
0.103 0.103 0.238 0.238 0.137 0.378               CROP PRICE ($/KG)
0.103 0.103 0.238 0.238 0.137 0.426               CROP PRICE ($/KG)
0.103 0.103 0.238 0.238 0.137 0.520               CROP PRICE ($/KG)
0.103 0.103 0.238 0.238 0.137 0.568               CROP PRICE ($/KG)
```

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BIOGRAPHICAL SKETCH

You Jen Tsai was born January, 1954, in Kaoshung, Taiwan, Republic of China. He attended and was graduated from Kaoshung High School in 1973. He enrolled at National Chung-Hsing University, Taichung, Taiwan, and received his Bachelor of Science degree in agricultural engineering in 1978. He continued his education at Clemson University, Clemson, South Carolina, and received his Master of Science degree in agricultural engineering in 1981. He enrolled at The University of Florida, Gainesville, in January 1982. You Jen is married to Chin Mei Wu, and they have one child, Hubert Jeng Yowe.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

J. W. Jones

J. W. Jones, Chairman
Professor of Agricultural Engineering

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J. W. Mishoe

J. W. Mishoe, Cochairman
Professor of Agricultural Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

K. L. Campbell

K. L. Campbell
Associate Professor of Agricultural Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Don Hearn

D. W. Hearn
Professor of Industrial and Systems Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Chung-Yee Lee

C. Y. Lee
Assistant Professor of Industrial and Systems Engineering

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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D J Shafer

Dean, College of Engineering

Dean, Graduate School